Recent progress in spin physics: Theoretical overview

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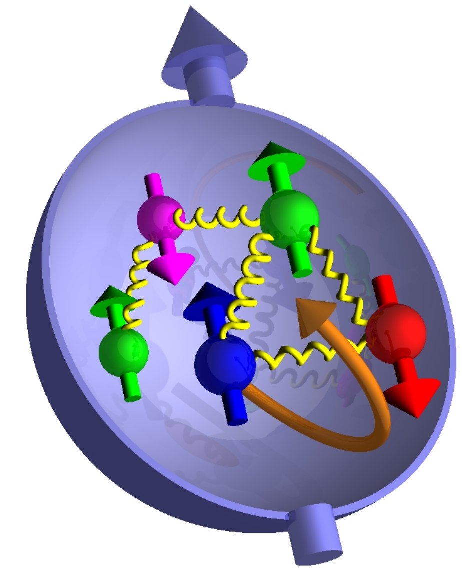
Outline

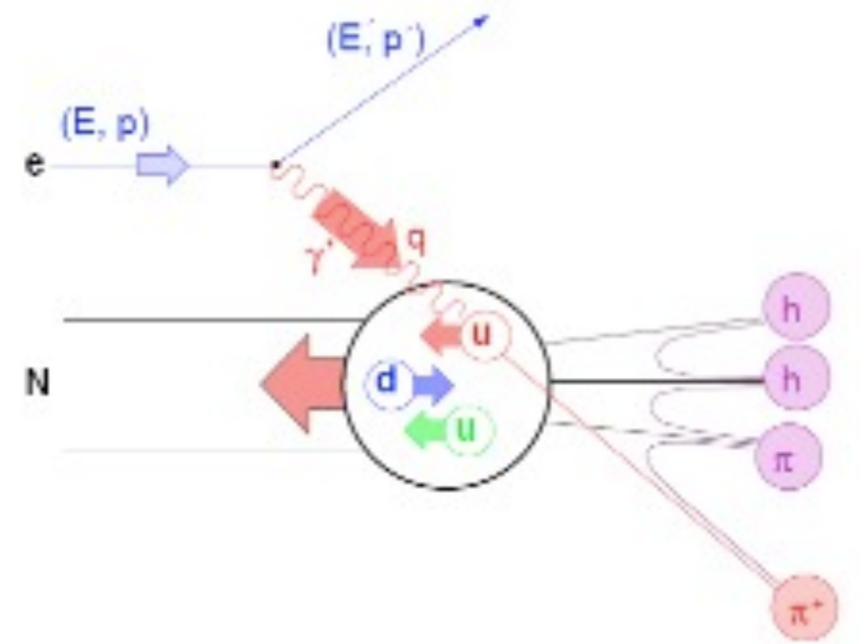
- Introduction
  - QCD factorization and hadron structure
- Longitudinal spin
  - Gluon helicity distribution
  - W program (quark and anti-quark helicity distribution)
- Transverse spin
  - Sign change and sign mismatch
  - QCD evolution of TMDs
- Summary

QCD factorization: a way to probe hadron structure

- We want to understand hadron structure in terms of quarks and gluons
  - longitudinal momentum distribution: collinear PDFs/HDFs
  - transverse momentum distribution: TMDs



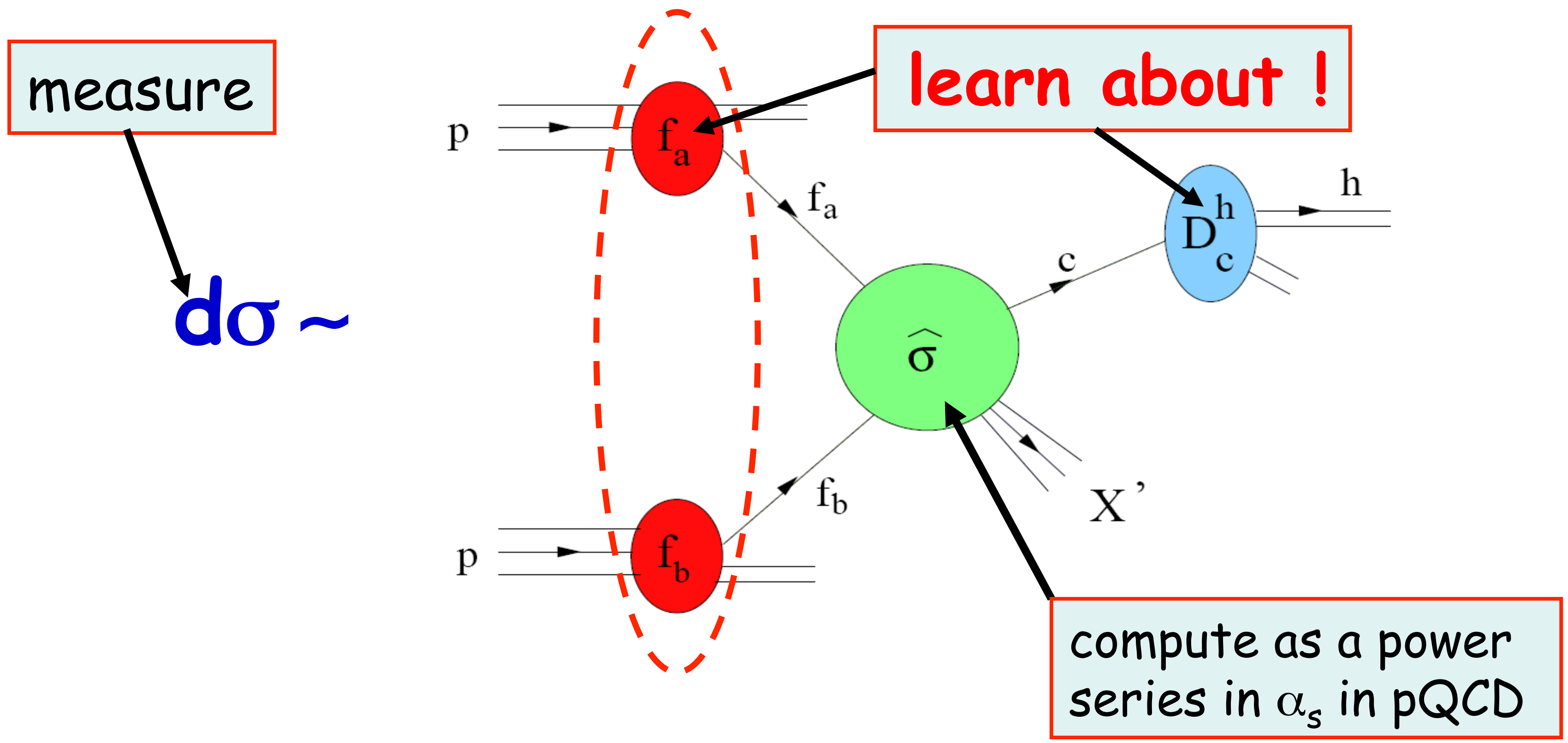
- To extract information on hadron structure, we send a probe and measure the outcome of the collisions
  - in order to trace back what's inside hadron from the outcome of the collisions, we rely on QCD factorization



- QCD factorization
  - collinear factorization: $pp \rightarrow h+X$ at high pt
  - TMD factorization: SIDIS, DY, $e^+e^- \rightarrow h_1h_2+X$
  - They are closely related to each other

QCD factorization: an example

- Factorization: $p + p \to \pi + X$
  - Hadron structure: encoded in PDFs
  - QCD dynamics at short-distance: partonic cross section

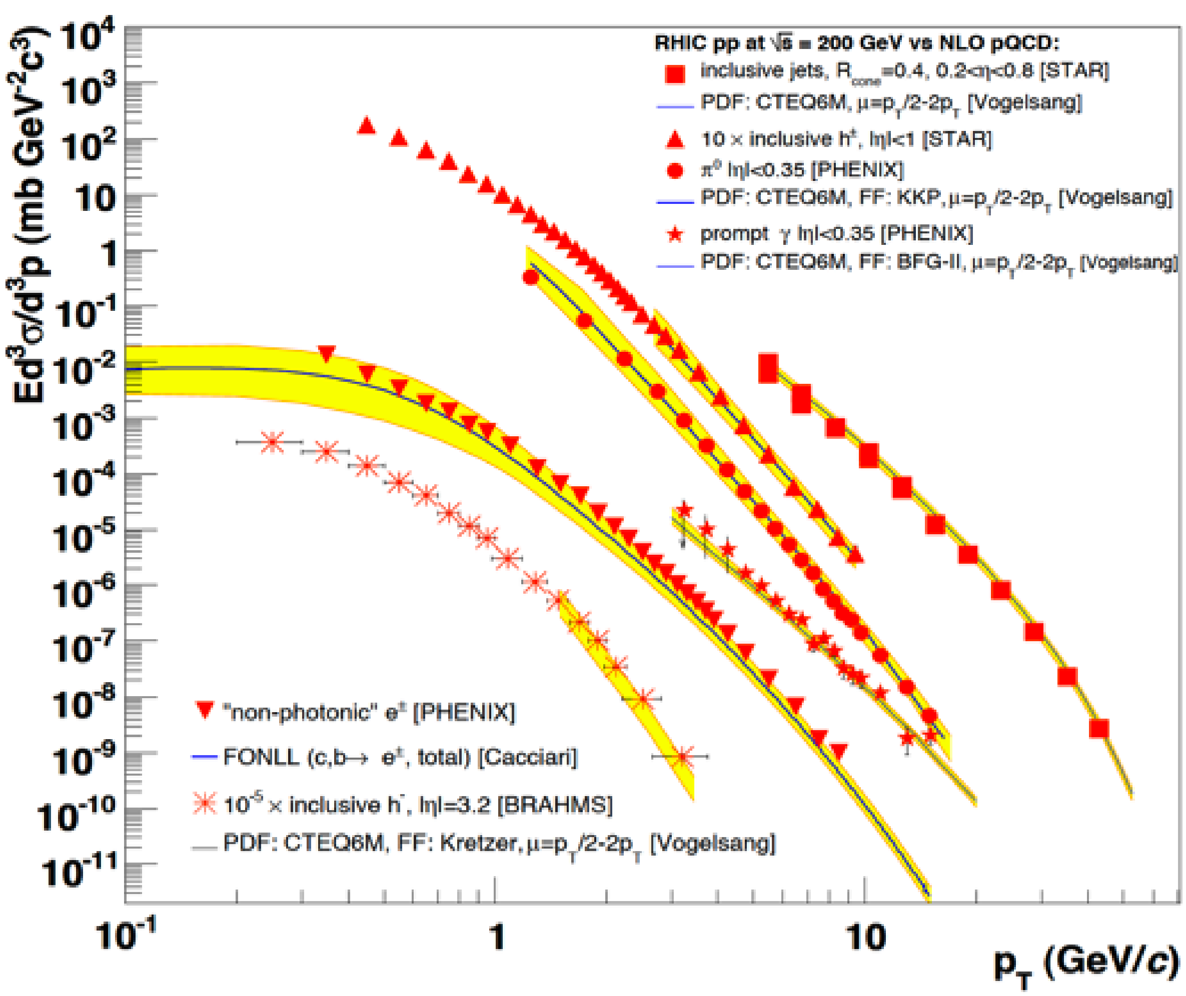


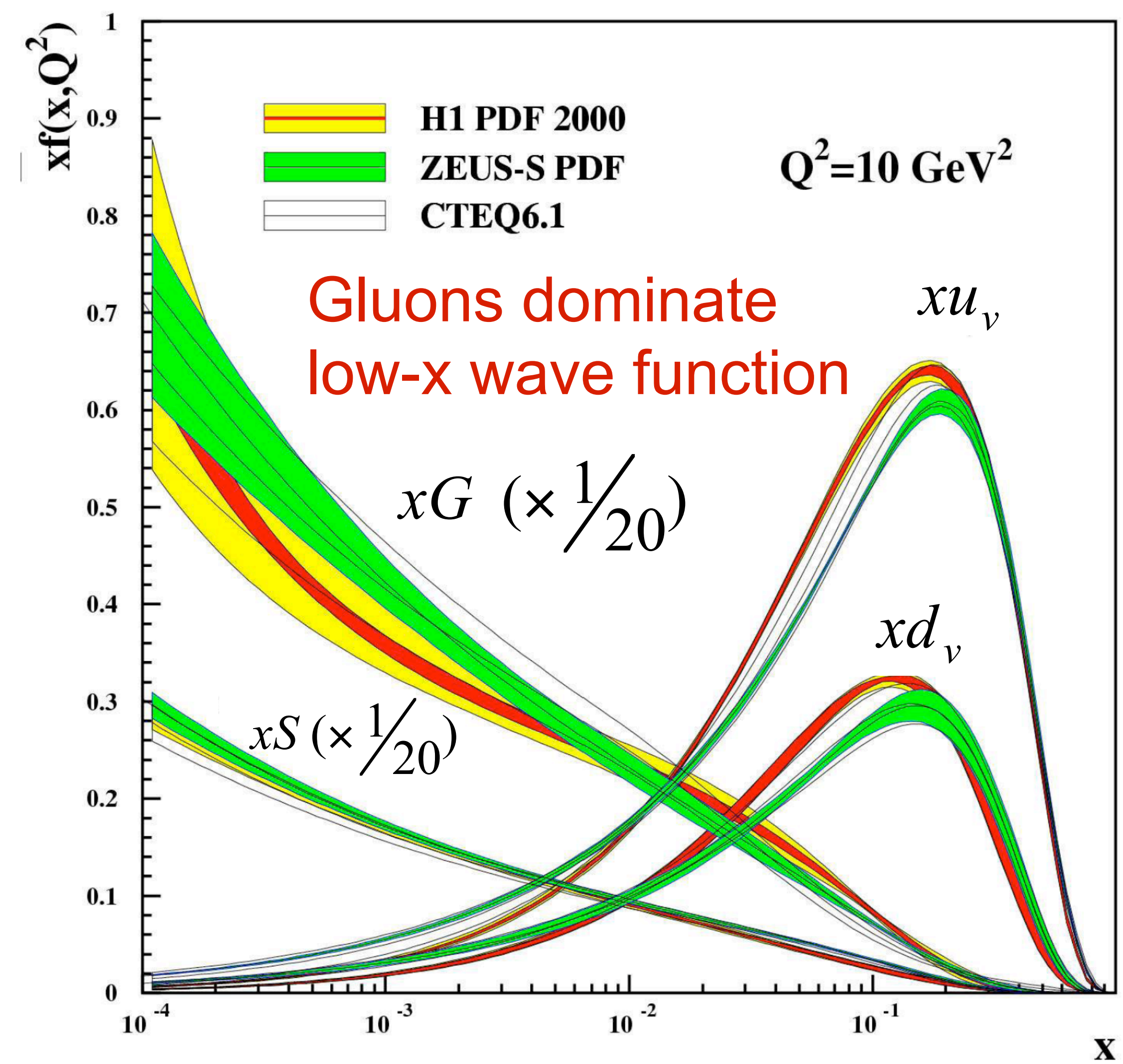
$$\sigma(P_h, S) \propto f_a(x_a, \mu^2) \otimes f_b(x_b, \mu^2) \otimes \hat{\sigma}_{ab\to c} \otimes D_{h/c}(z_c, \mu^2)$$

Universal **Universal** **calculable** **Universal**

Successful picture

- Emerged around 1980s, this picture has been very successful
  - measure PDFs in all x region as precise as possible
  - higher order / resummation for short-distance
  - essential for physics beyond standard model

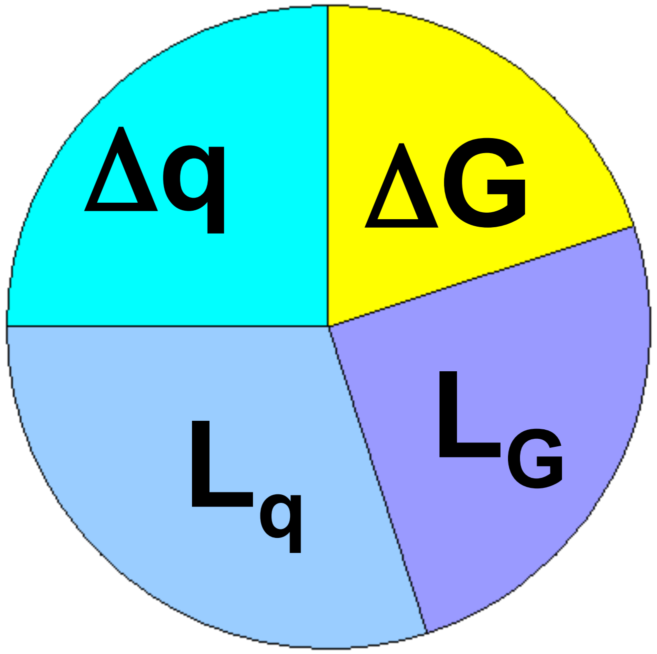




Spin structure of the proton

- At RHIC, we like Jaffe-Manohar decomposition (there are many more)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



  - $\Delta\Sigma$: quark spin
  - ΔG : gluon spin
  - L_q : quark orbital angular momentum
  - L_g : gluon orbital angular momentum

- Through longitudinal polarized DIS, SIDIS and pp collisions, we could extract $\Delta\Sigma$ and ΔG.
- In the past, we don't know how to extract OAM. The only way is to use 1/2 subtract quark and gluon spin.
- Most recent development: quark and gluon OAM can be related to the matrix element of twist-3 GPDs. Thus in principle it could be measured in the experiments

Ji-Xiong-Yuan, arXiv: 1202.2843

How to probe quark spin contribution

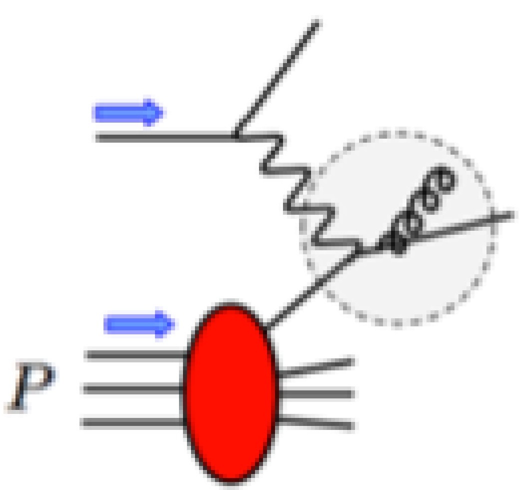
- Quark helicity distributon:

$$\Delta q(x, \mu^2) =$$

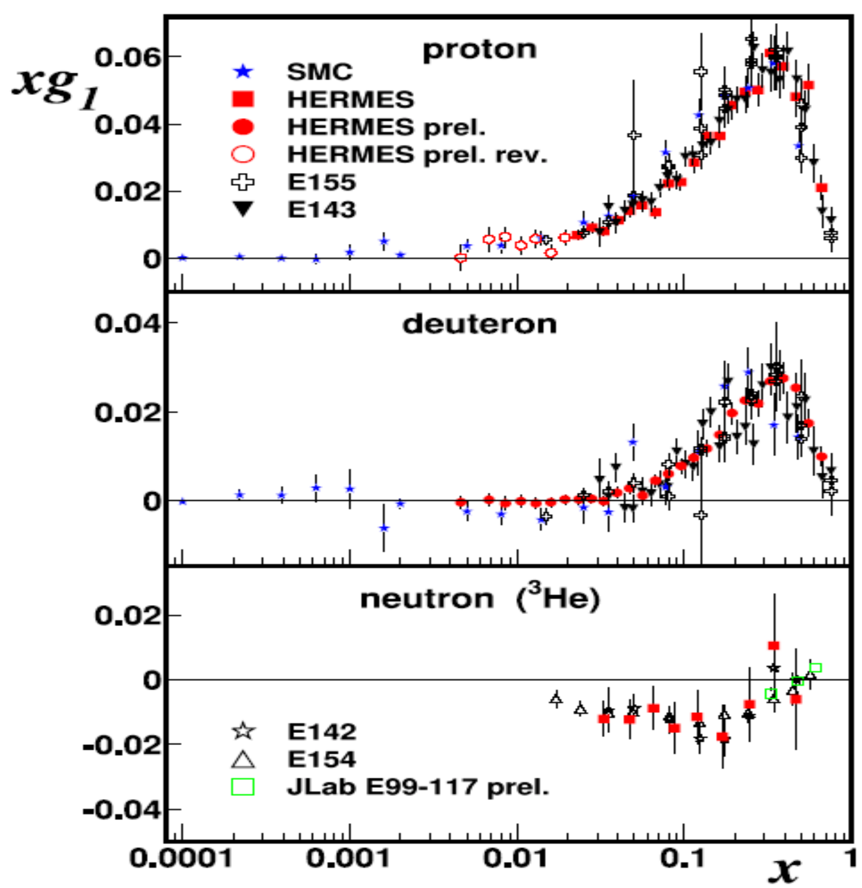
- Quark spin contribution: $\Delta\Sigma = \int_0^1 dx\, [u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + s(x) + \bar{s}(x)]$

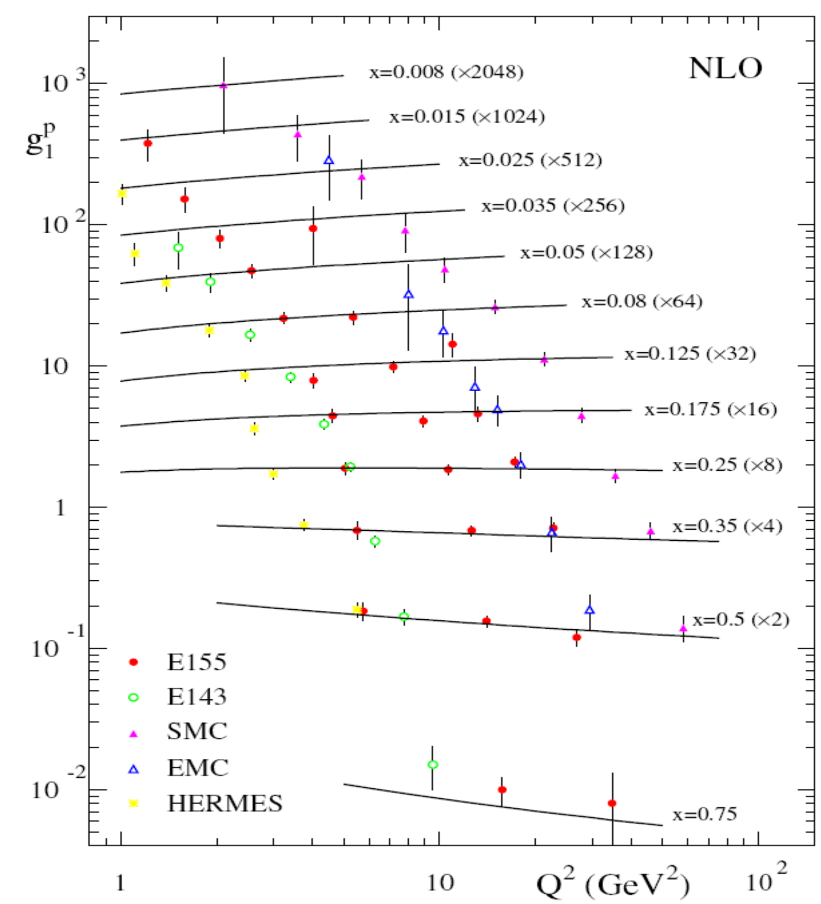
- DIS and SIDIS: make precise measurements of ΔΣ

$$\sigma^{\stackrel{\rightarrow}{\Leftarrow}} - \sigma^{\stackrel{\rightarrow}{\Rightarrow}} \propto g_1(x, Q^2) = \sum_q e_q^2 \left[\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2)\right]$$



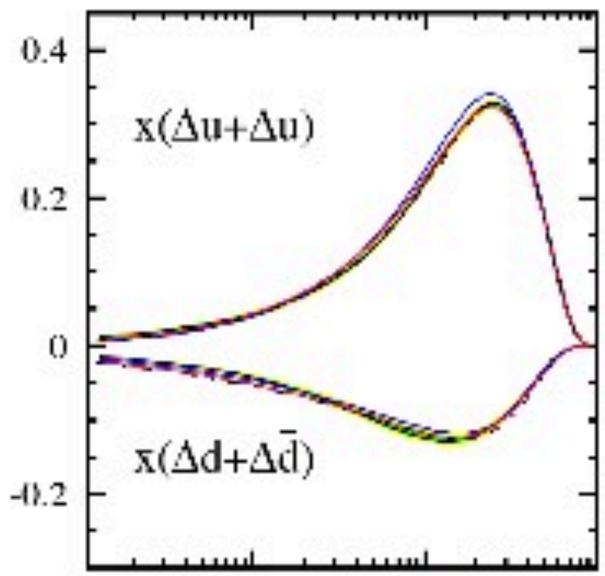
DIS

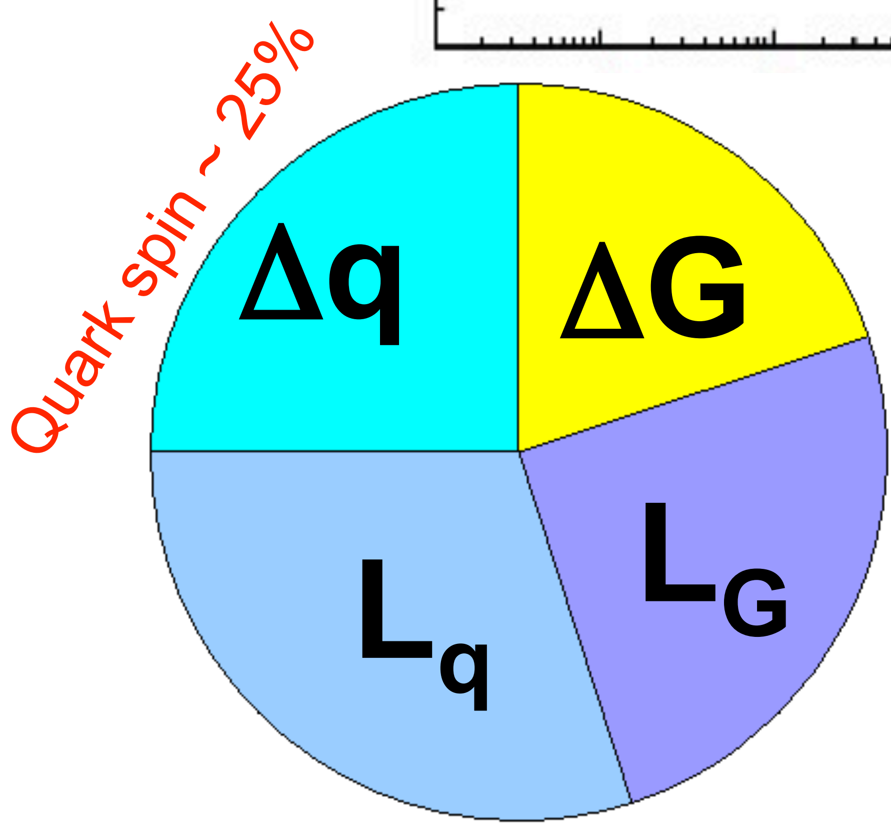


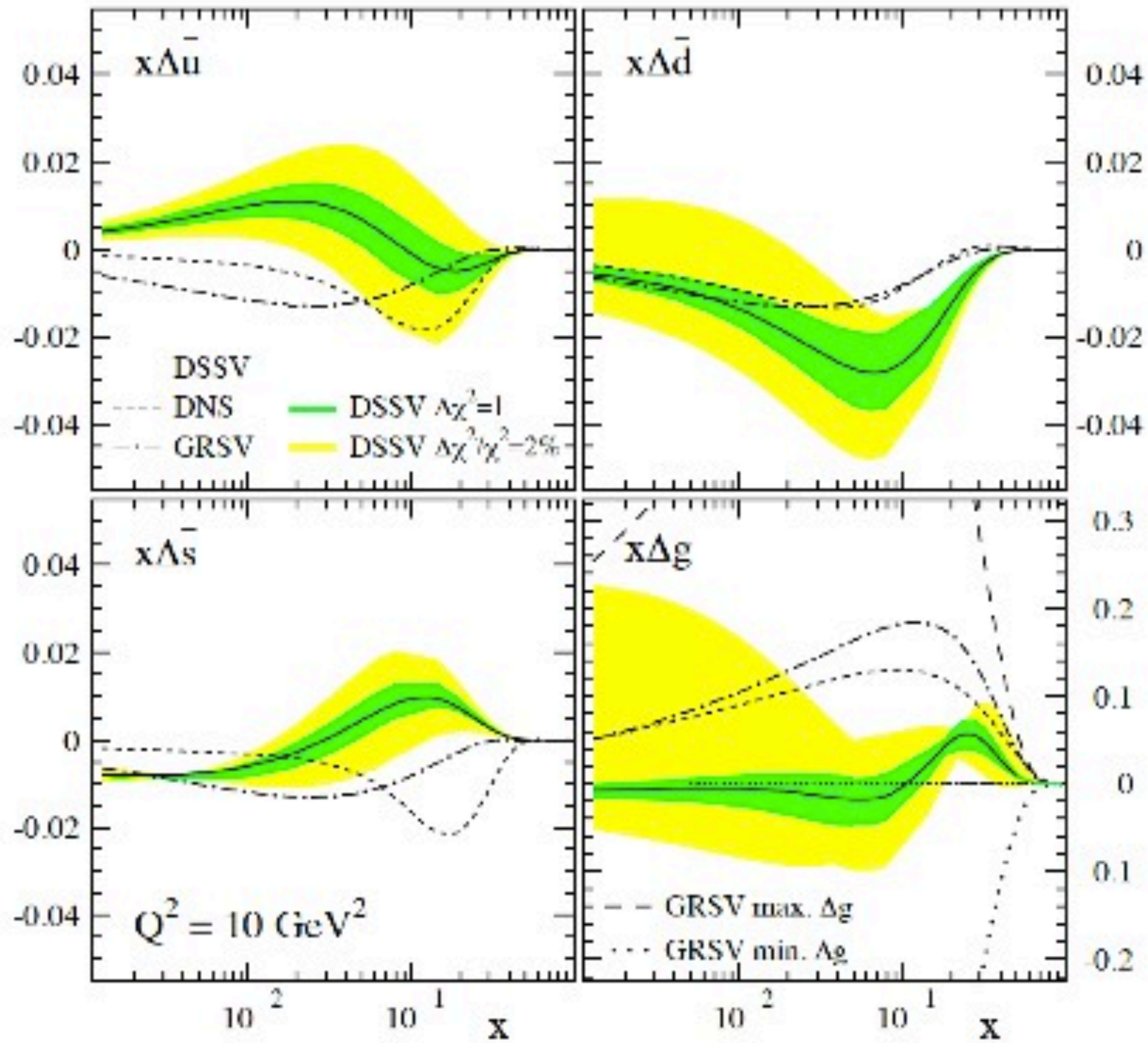


Best determined quark helicity distributions

- Best determined: valence quark Δu, Δd

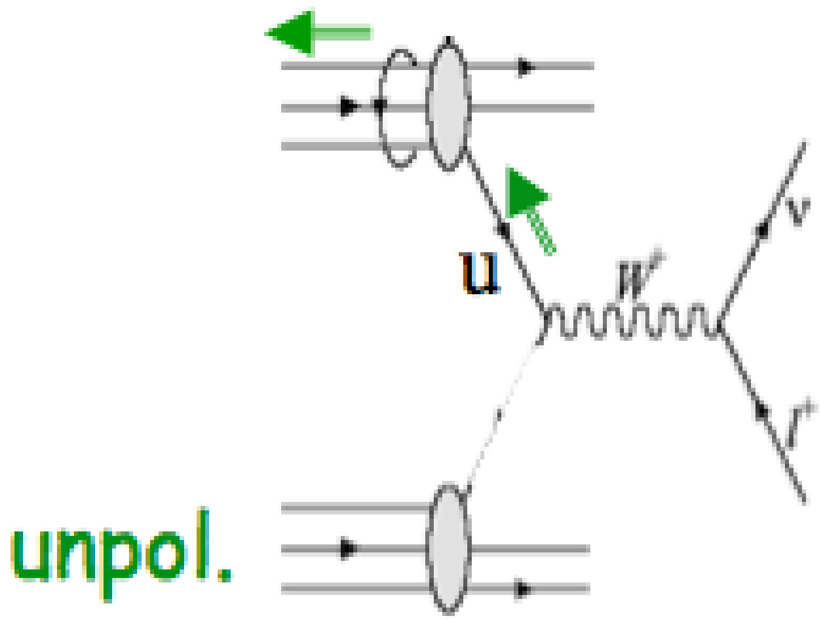




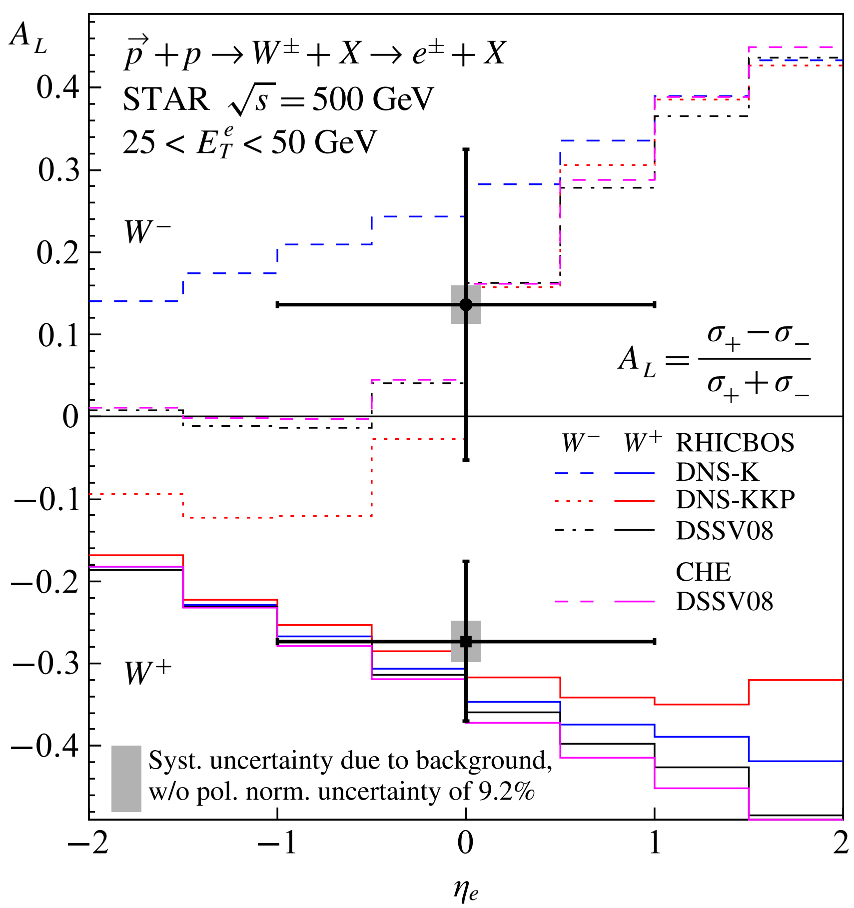


- Remaining issues: what about sea quark and gluon contributions?

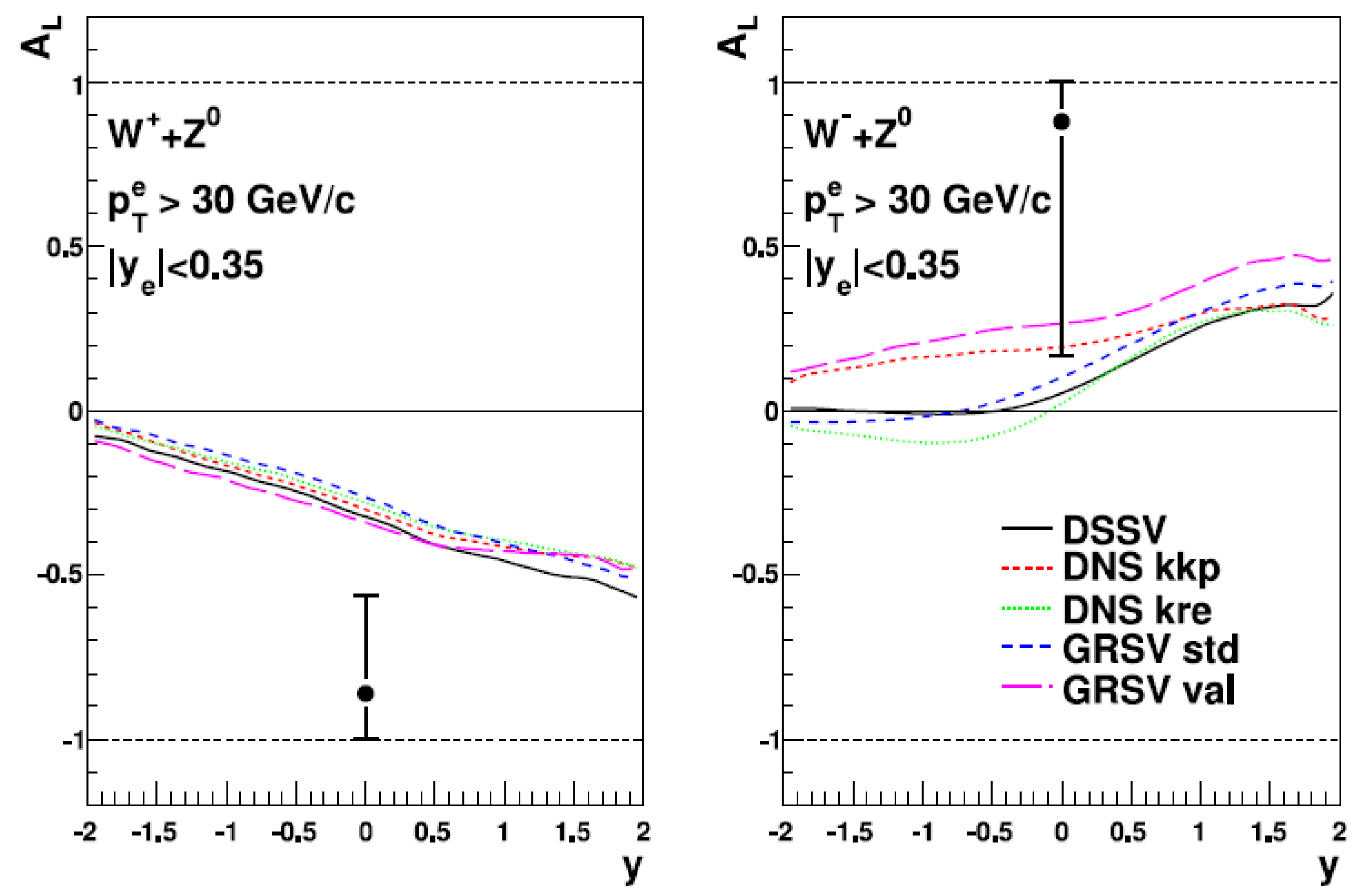
Sea quark spin contribution: 500GeV W program at RHIC



Parity violation: A_L exist $\propto \Delta\bar{q}$
Flavor separation



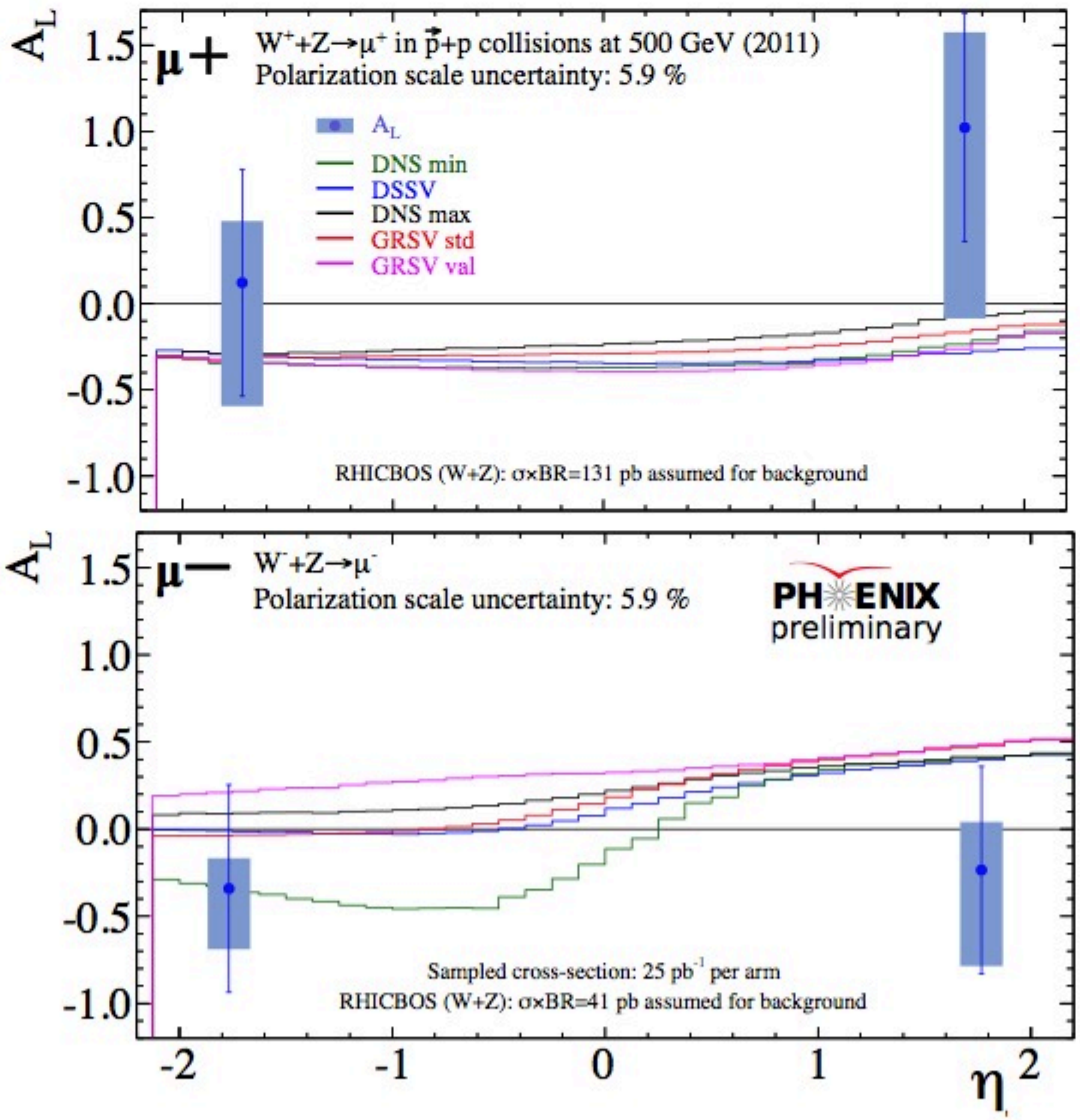
STAR, PRL, 2010



PHENIX, PRL, 2010

Most recent result for W asymmetry (2012)

- A_L in forward rapidity



Positivity bound for spin asymmetry

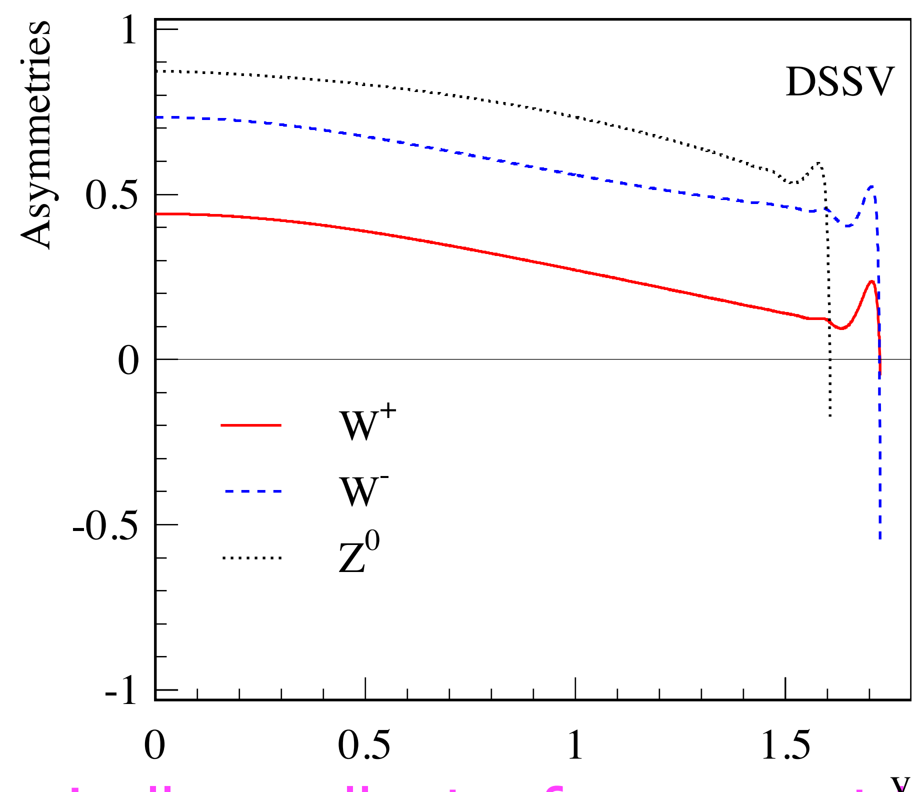
- Based on the positivity of the cross section, we derived the following inequality (for W/Z or leptons decayed from them):

$$|A_L(y) \pm A_L(-y)| \leq 1 \pm A_{LL}(y)$$

Kang-Soffer, 1104.2920, PRD83, 2011

- It is not trivial to satisfy such a bound, e.g., DSSV at large y

$$1 + A_{LL}(y) - |A_L(y) + A_L(-y)| \geq 0$$



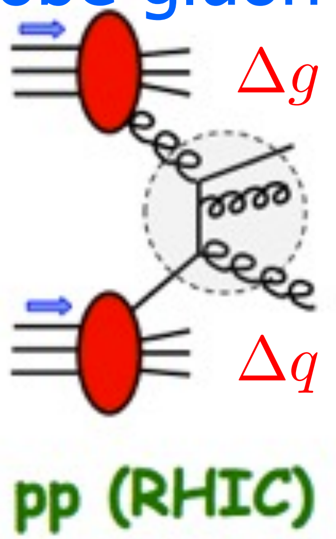
- Interesting to check experimentally
  - at mid-rapidity y=0, we have ($A_{LL}(0)$ is typically small, at a few percent level)

$$|A_L(0)| \leq \frac{1}{2}$$

  - current PHENIX seems to be out of this bound, though large uncertainty at the moment

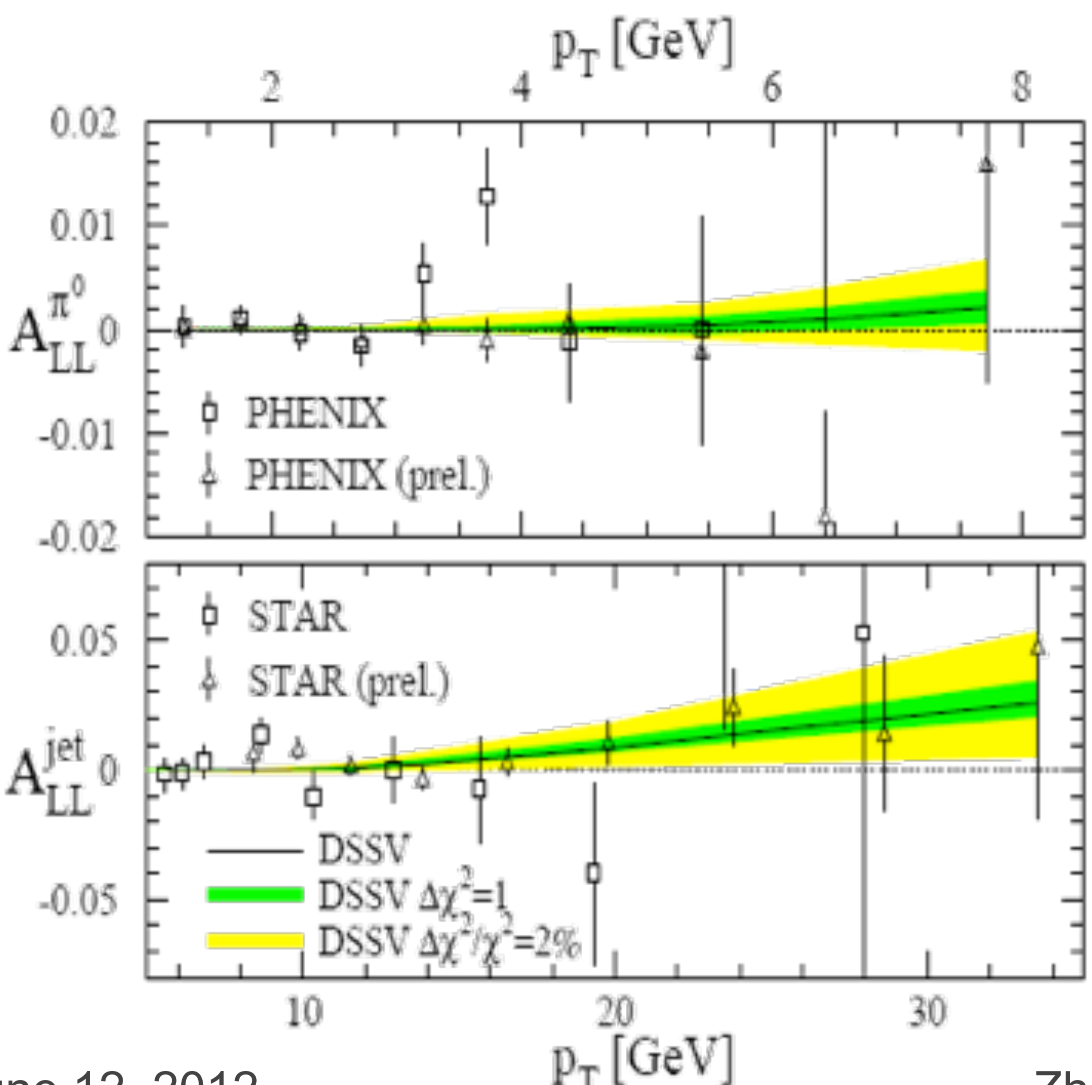
Gluon spin contribution: status 2009

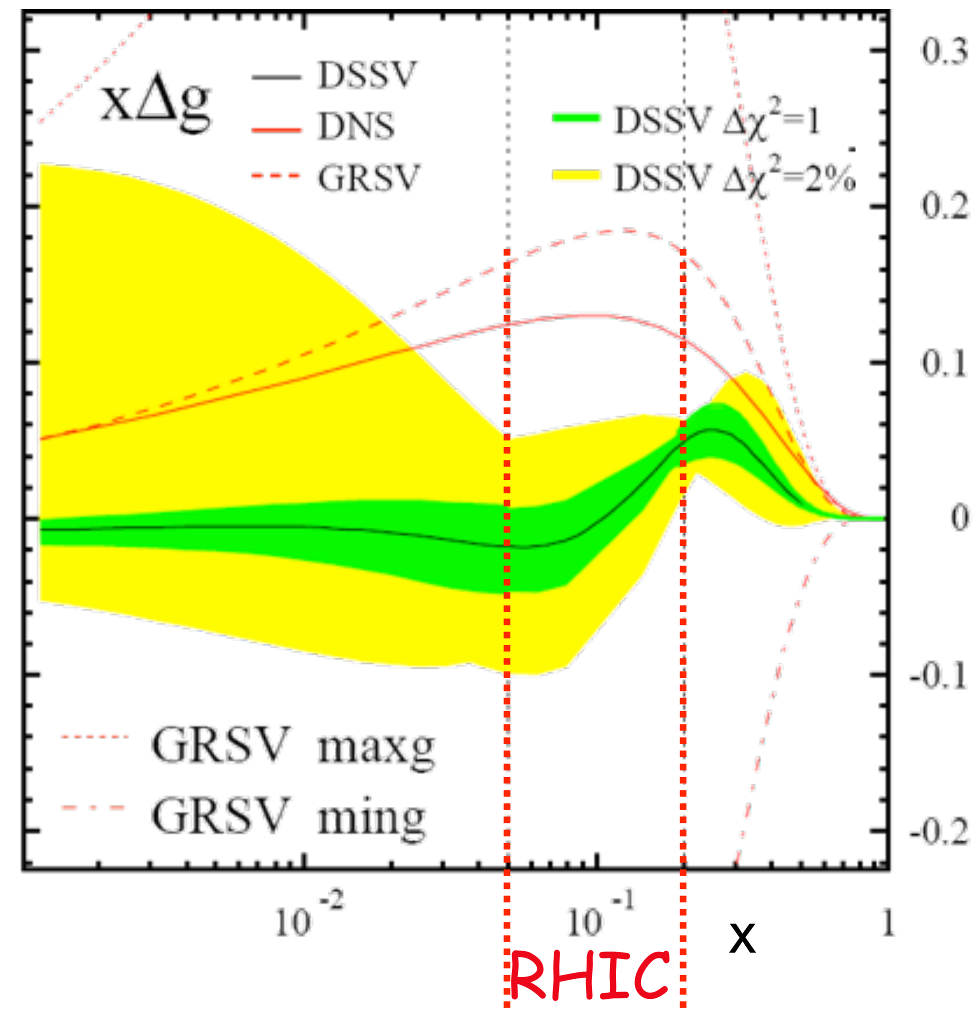
- Probe gluon spin at RHIC:



$$A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \equiv \frac{\Delta\sigma}{\sigma}$$

$$\Delta\sigma = \Delta f_a(x_a, \mu^2) \otimes \Delta f_b(x_b, \mu^2) \otimes \Delta\hat{\sigma}^{ab}$$



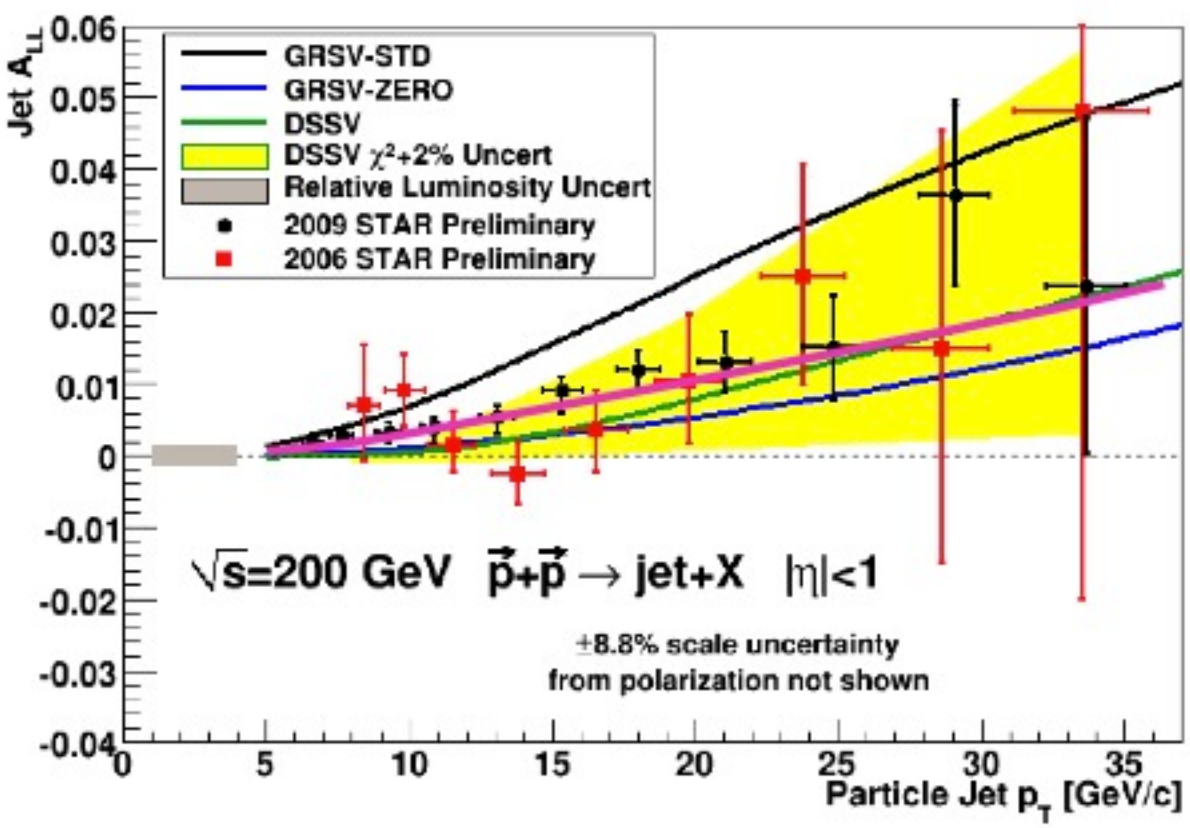


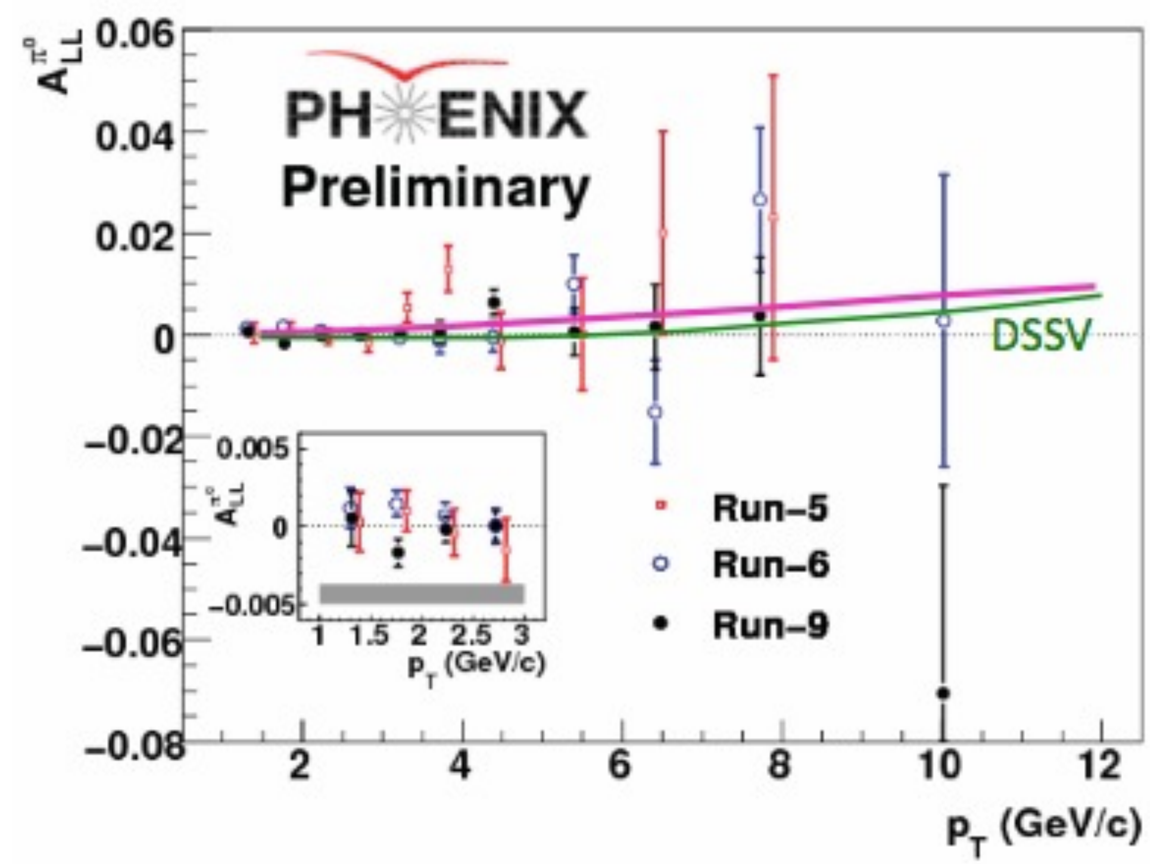
0.05 < x < 0.2

$$\Delta G = \int_{0.05}^{0.2} dx \Delta g(x) = 0.006 \pm 0.06$$

Gluon spin contribution: status 2011

- New data from SIDIS (COMPASS) and pp (STAR and PHENIX)
  - new COMPASS data is more or less consistent with DSSV parametrization
  - Δg is of course more sensitive to pp data





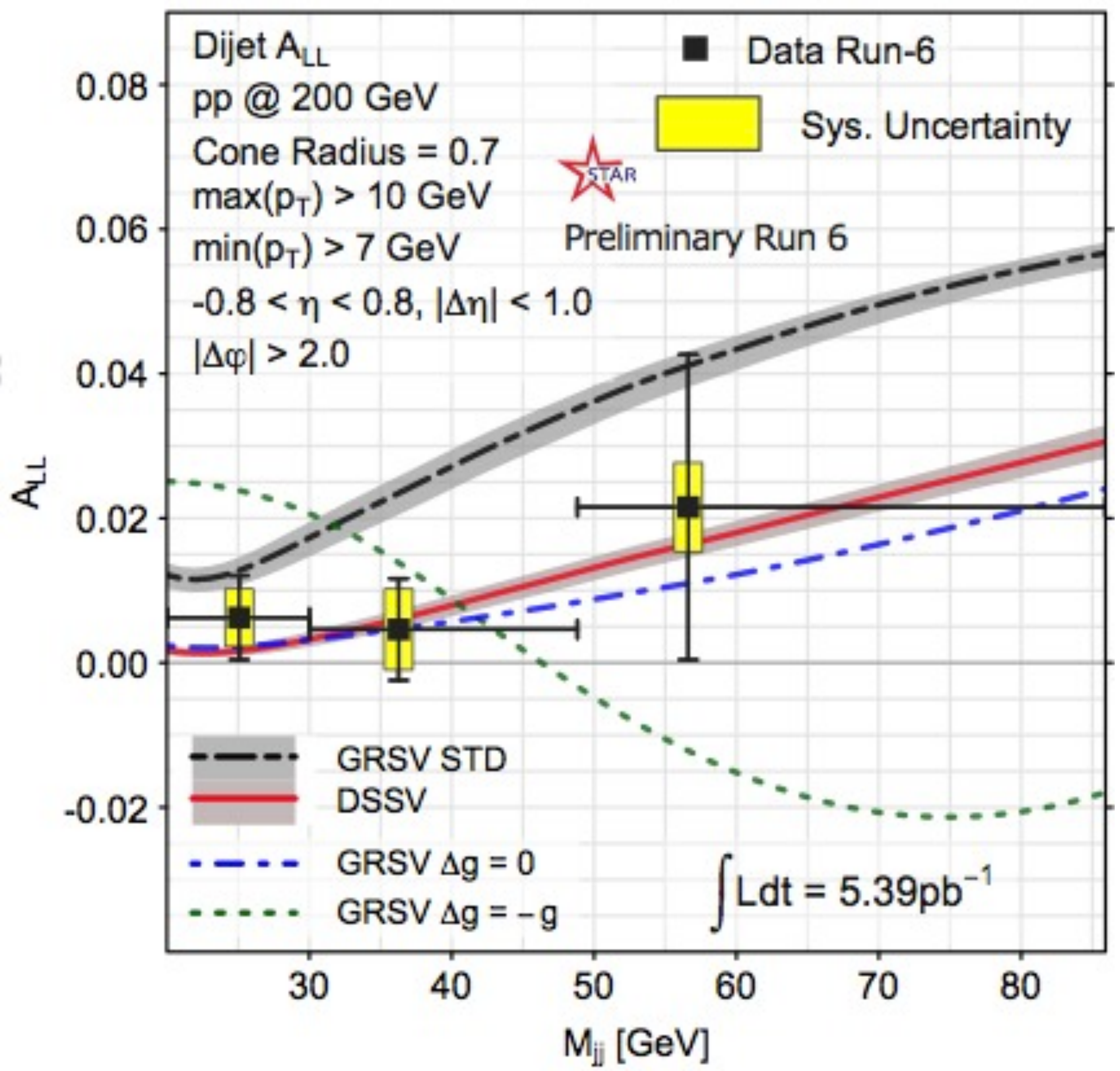
- First indication: non-vanishing gluon spin contribution

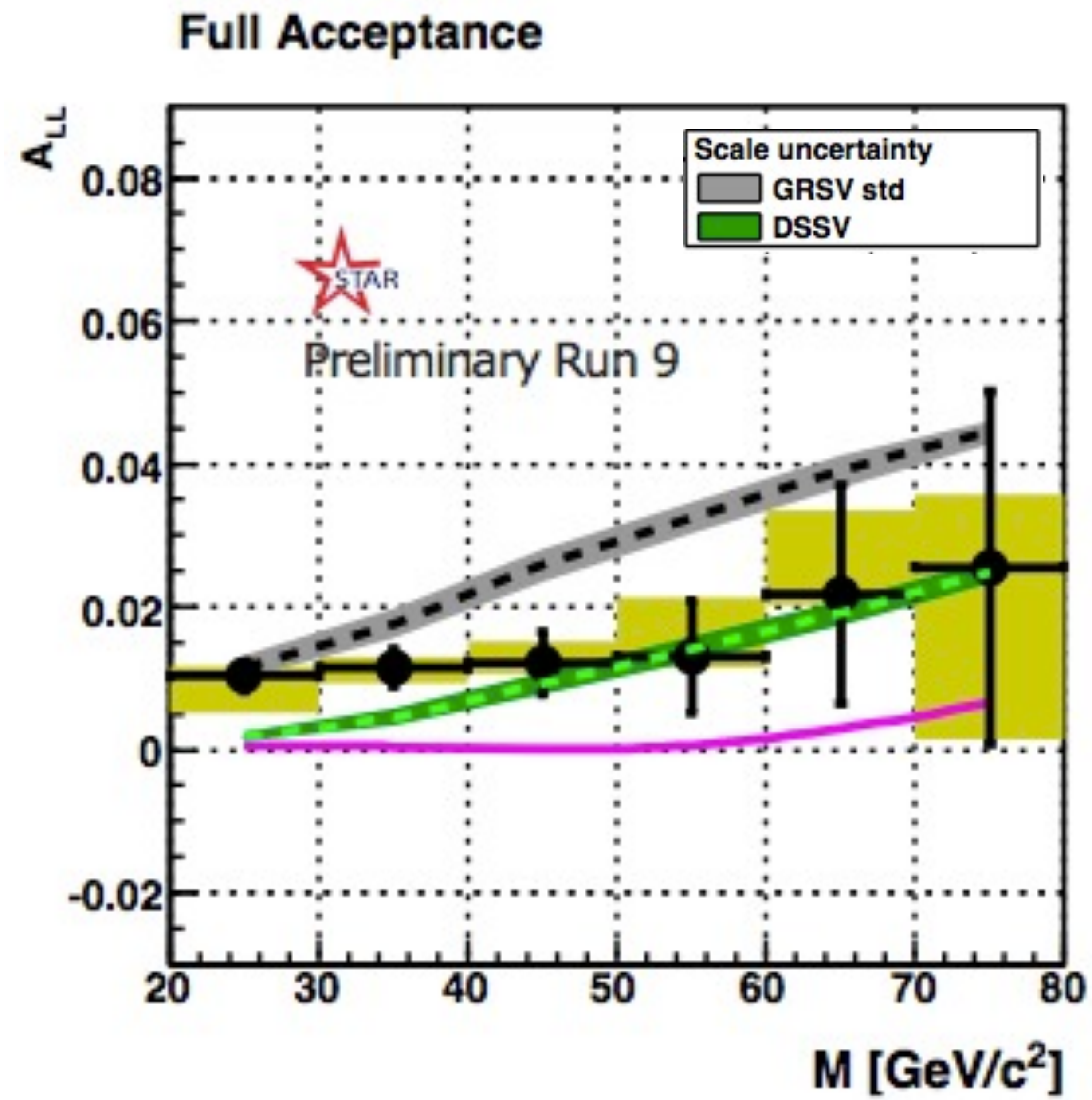
DSSV: arXiv 1112.0904

$$\Delta G = \int_{0.05}^{0.2} dx \Delta g(x, Q^2 = 10\text{GeV}^2) = 0.13$$

Most recent data from STAR (2012)

- Di-jet production





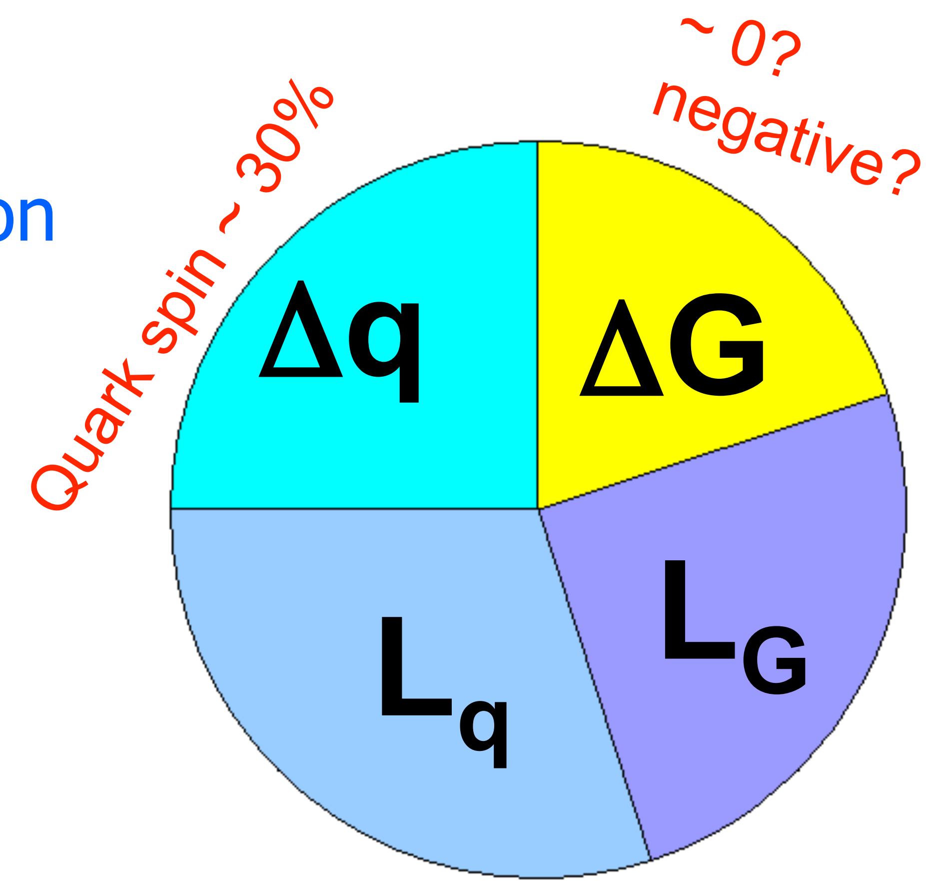
Proton spin budget

- What is the missing spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

- Big uncertainties on gluon spin contribution
  - Limit x range
  - node or not: node disappear? nonvanishing?

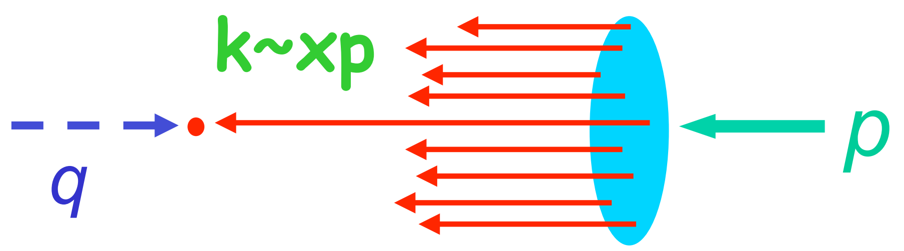
$$\Delta G = \int_0^1 dx \Delta g(x) = -0.084 \pm ?$$



- Question: if intrinsic spin of quarks and gluons does not contribute much to the proton spin, one needs to probe the orbital motion, need to exam the parton’s transverse motion in the proton

Parton's transverse motion

- Collinear factorization:
  - K_T-information is either integrated into PDFs (FFs) or neglected as power corrections



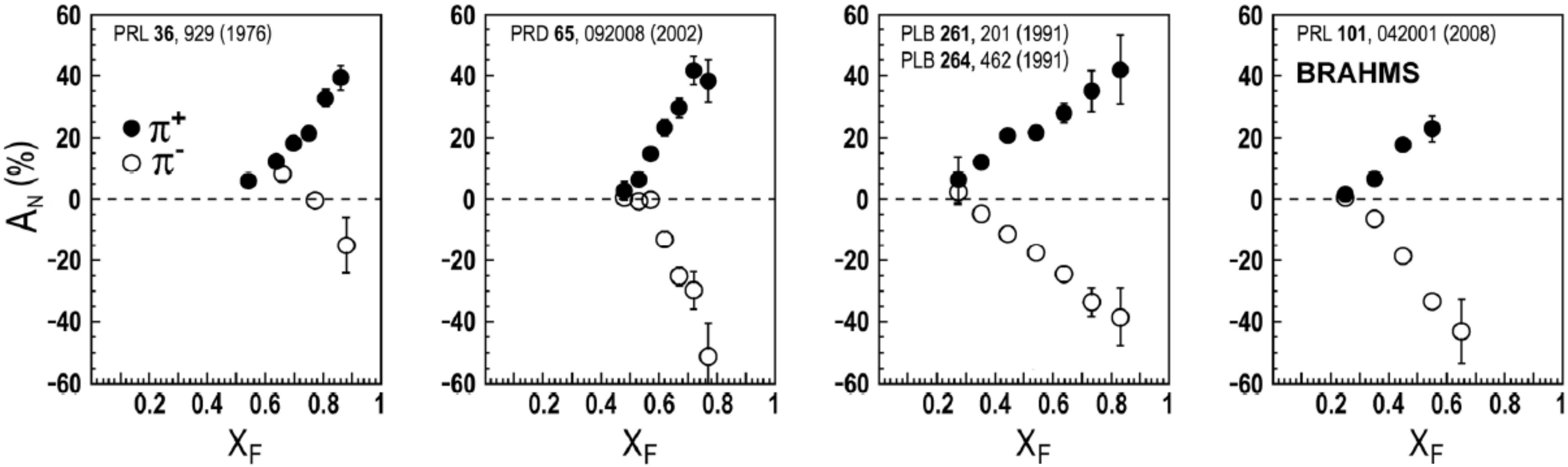
- Need to explore the observables that are sensitive to the parton's transverse motion

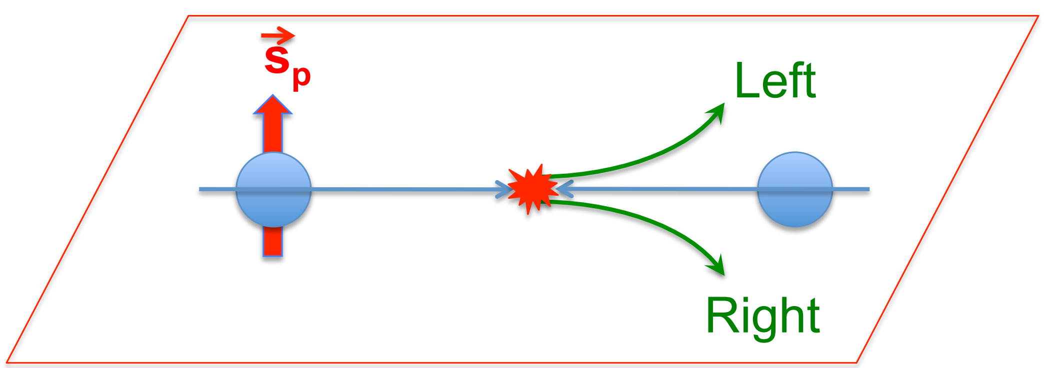
Transverse spin phenomena

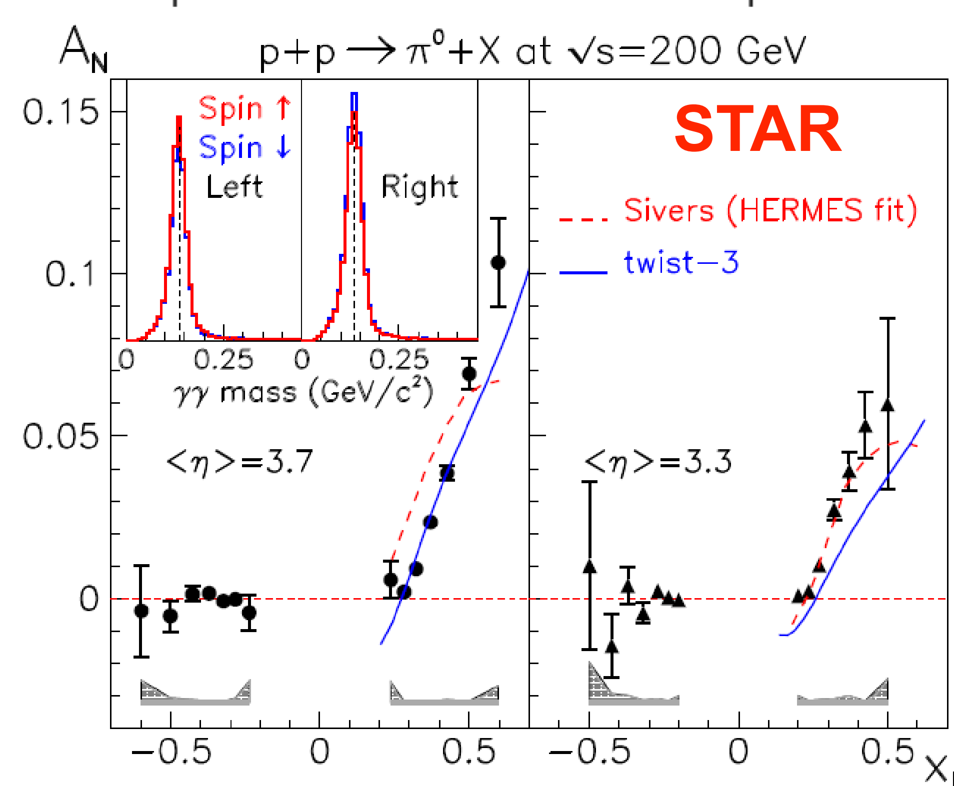
Single transverse-spin asymmetry (SSA)

- Consider a transversely polarized proton scatter with an unpolarized proton

ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV



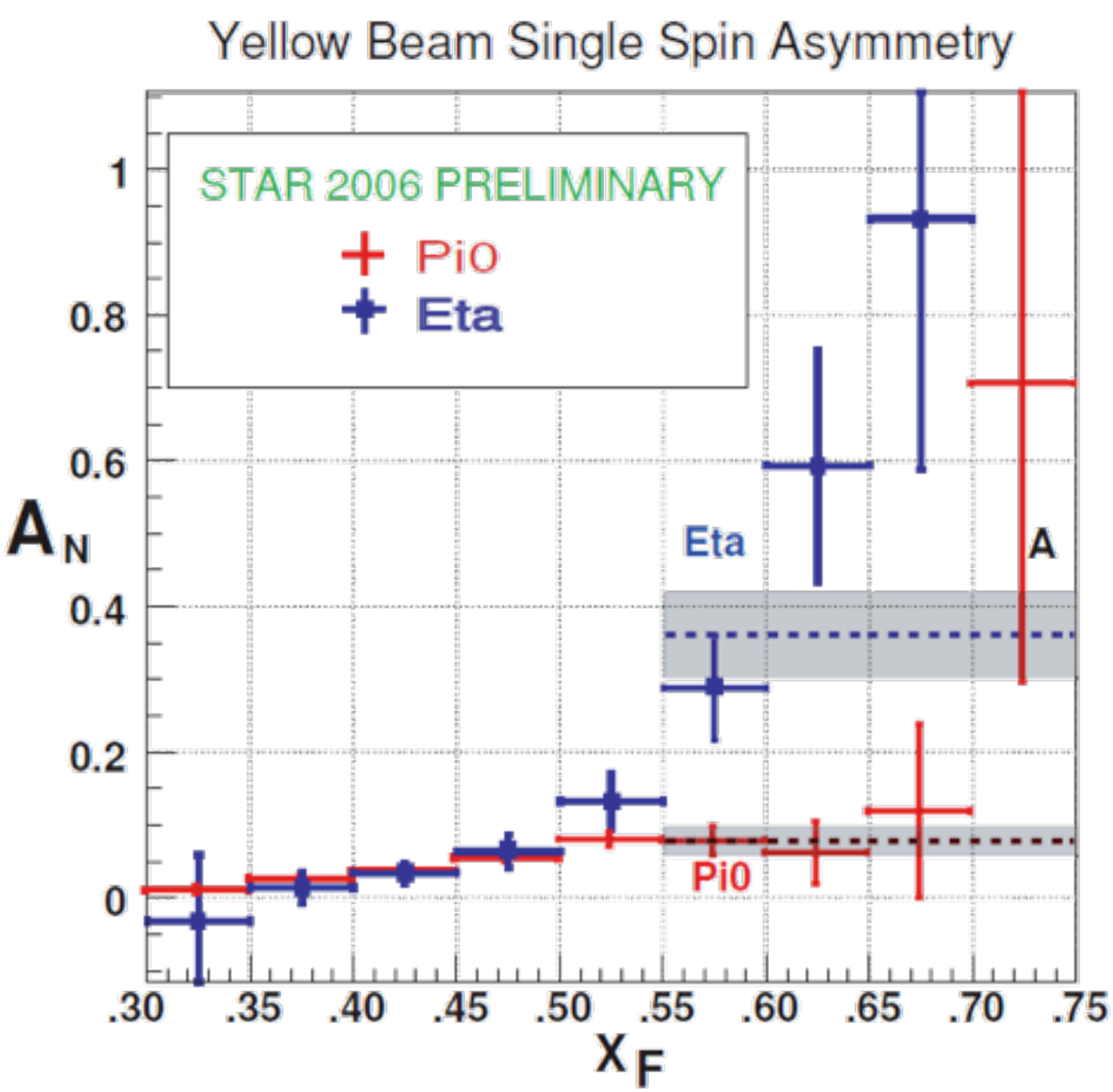




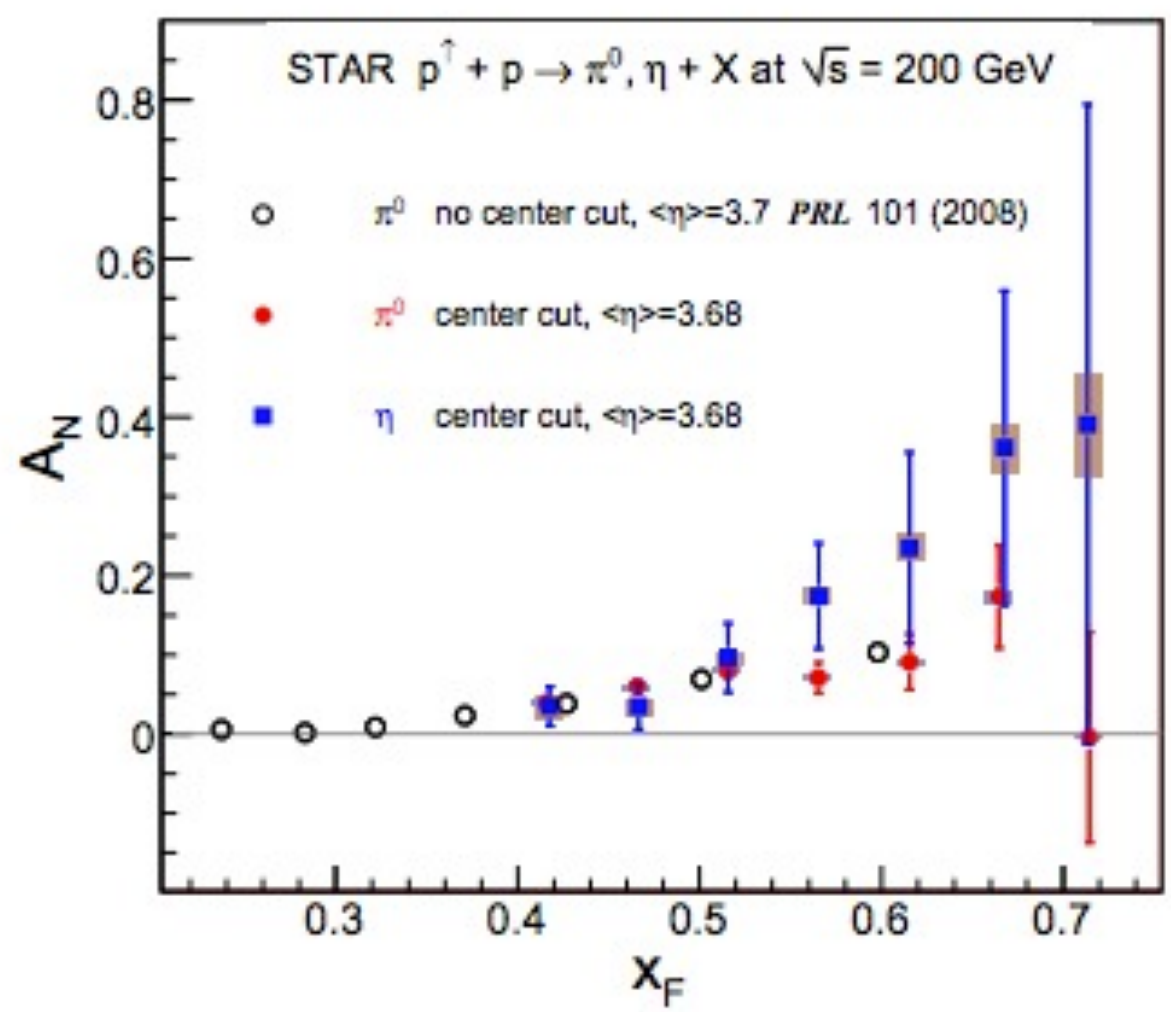
$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s})-\sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s})+\sigma(\ell,-\vec{s})}$$

Most recent experimental data

- SSA of single inclusive hadron is still the most difficult to understand. Fortunately, experiments are now consistent with each other

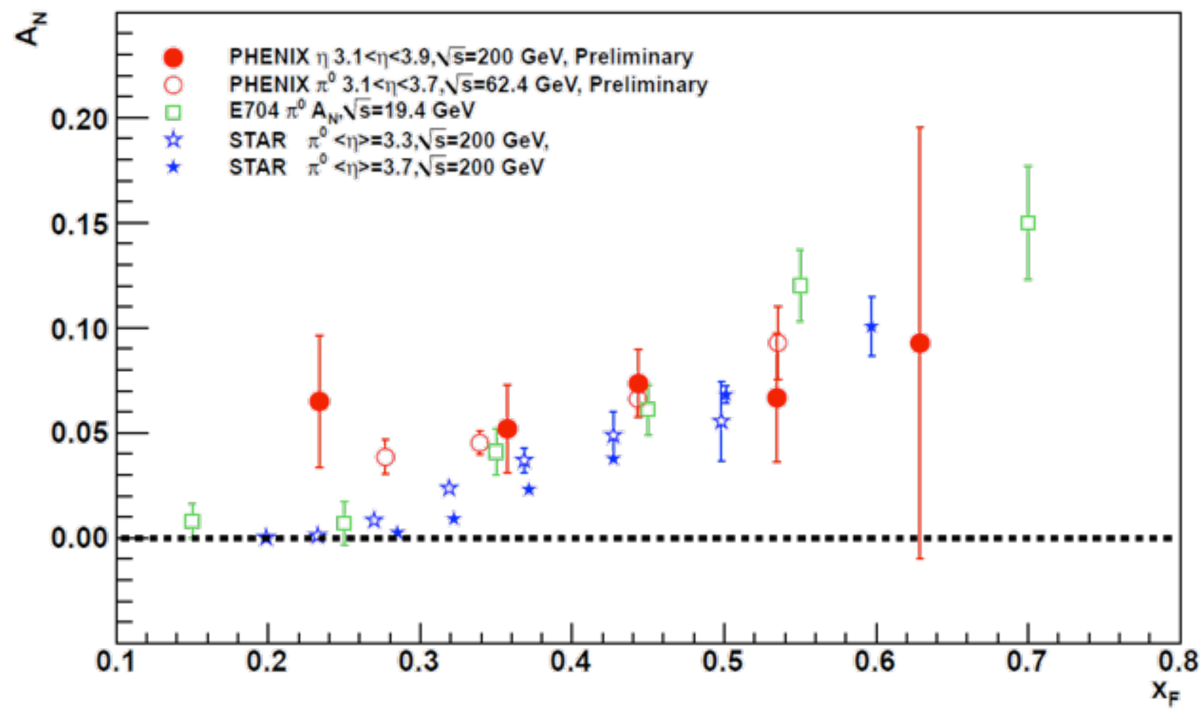


STAR, arXiv:1205.6826

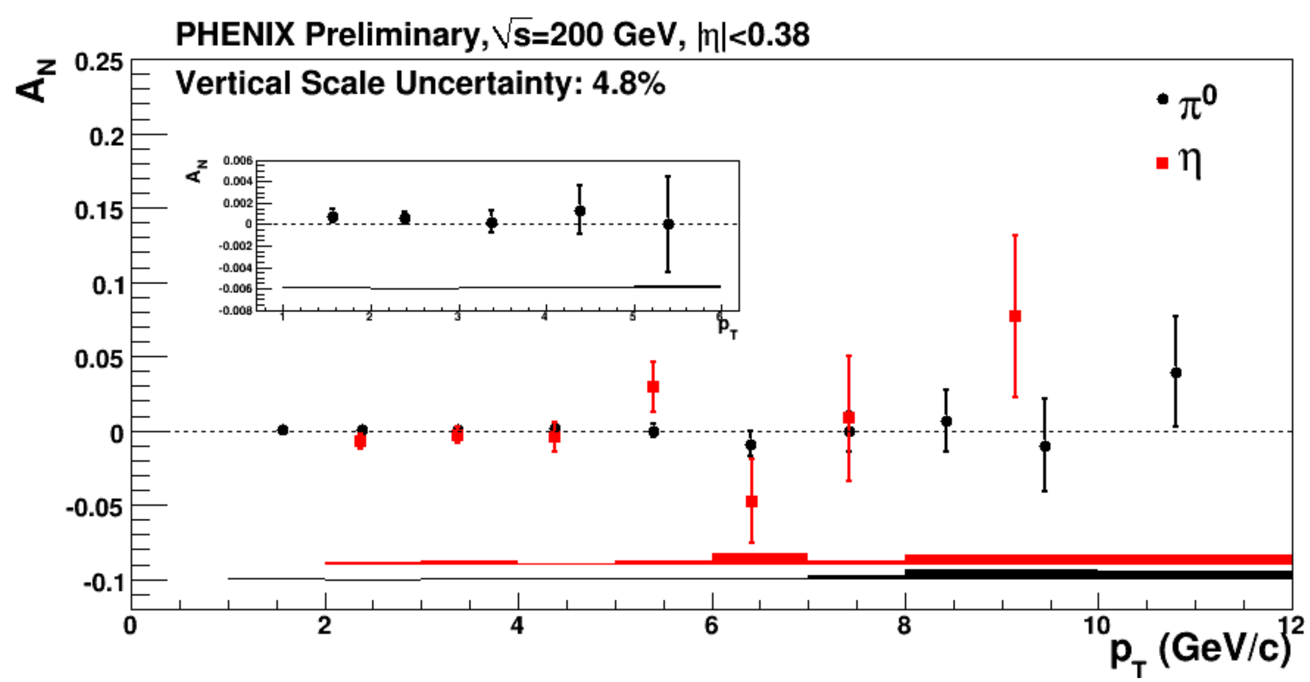


PHENIX measurements at forward rapidity

- forward rapidity: eta is more or less the same as pi0

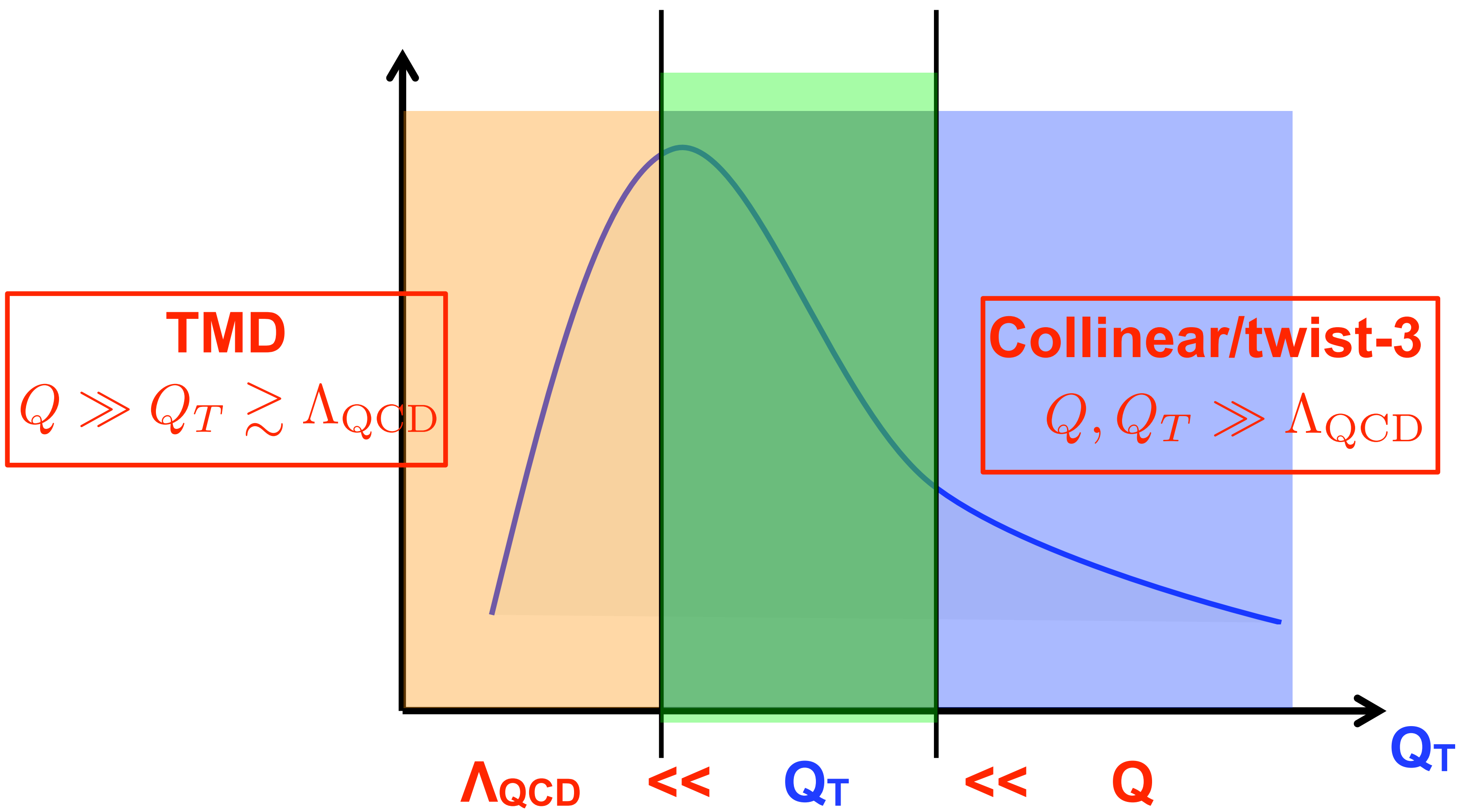


- mid rapidity



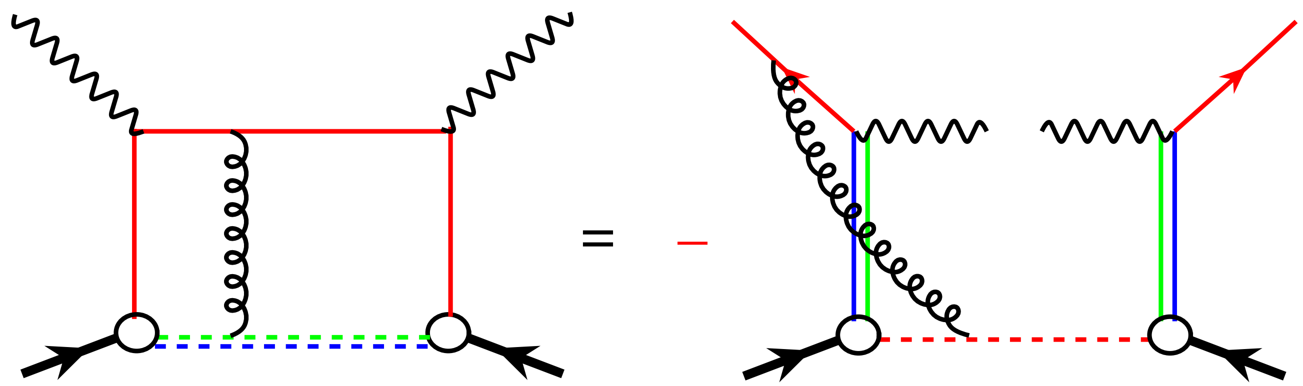
Understand SSA: related to parton transverse motion

- One could immediately think of two ways to include parton's transverse momentum into the formalism
  - Generalize the collinear distribution $f(x)$ to $f(x, k_\perp)$
  - Taylor expansion: $f(x, k_\perp) = f(x) + k_\perp f'(x) + \cdots$, where $f'(x) = df(x, k_\perp)/dk_\perp$ at $k_\perp = 0$, then ∫d²kt kt f′(x) = a higher-twist correlation
- The first one is called TMD approach, the second one is called collinear twist-3 approach. They are closely related to each other.

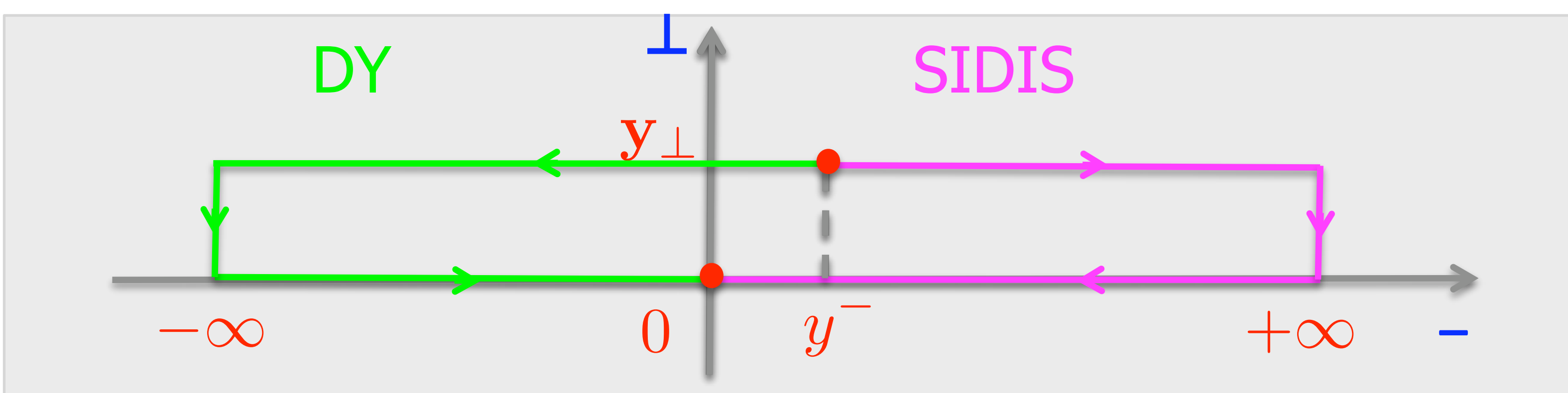


Physics of gauge link

- Rescattering (gauge link) determined by hard process and its color flow



SIDIS = – DY



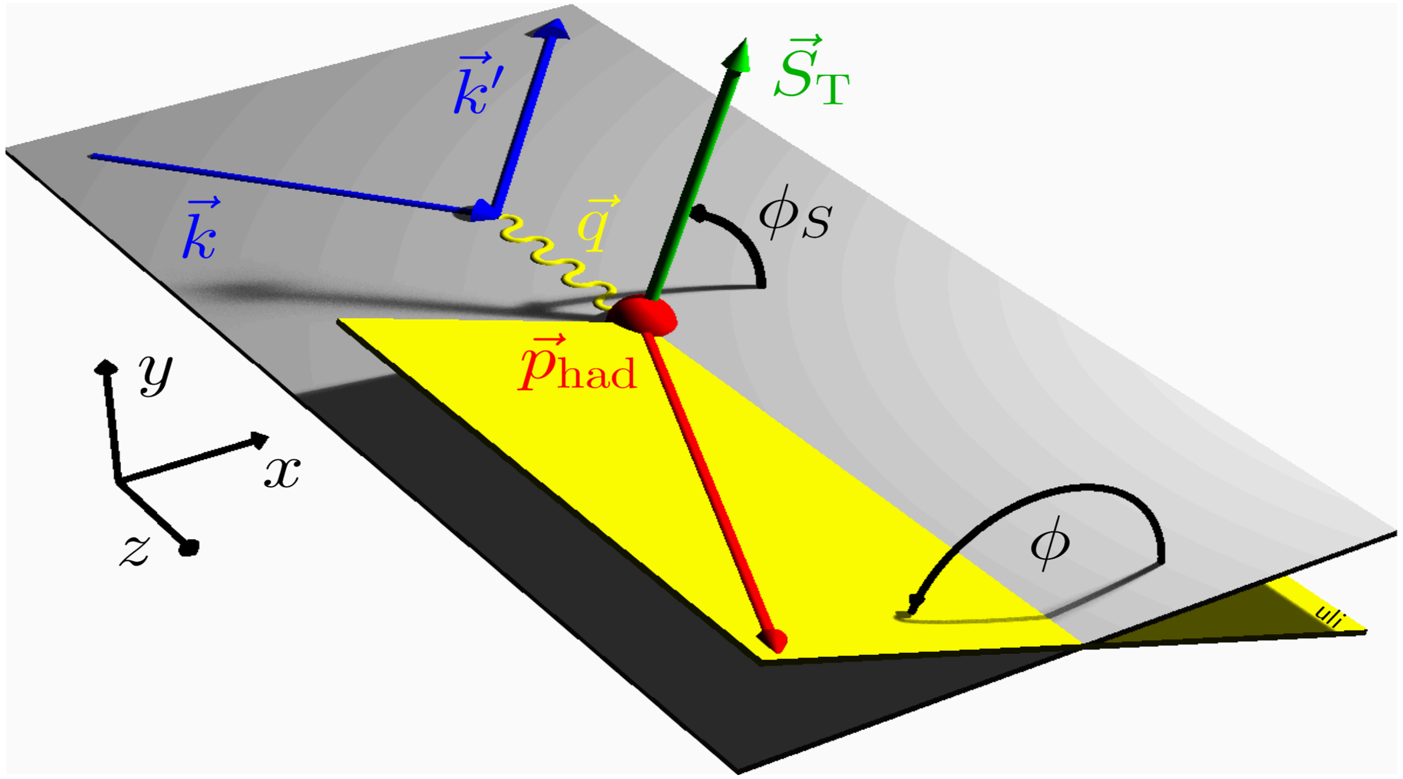
$$\Delta^N f^{\mathrm{SIDIS}}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\mathrm{DY}}_{q/h^\uparrow}(x,k_\perp)$$

Central quest for the field at the moment

Current Sivers function from SIDIS

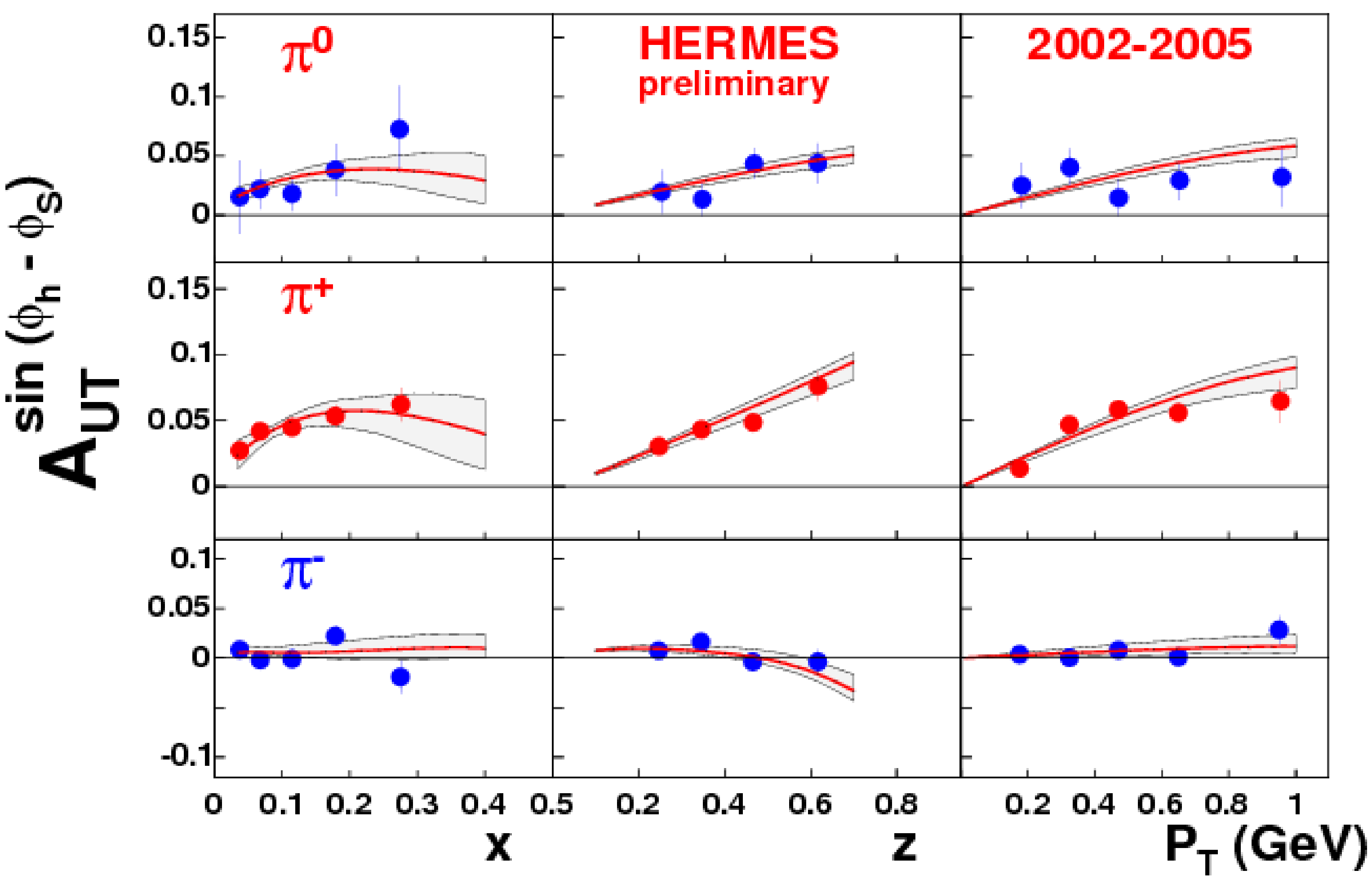
- Sivers and Collins can be separately extracted from SIDIS

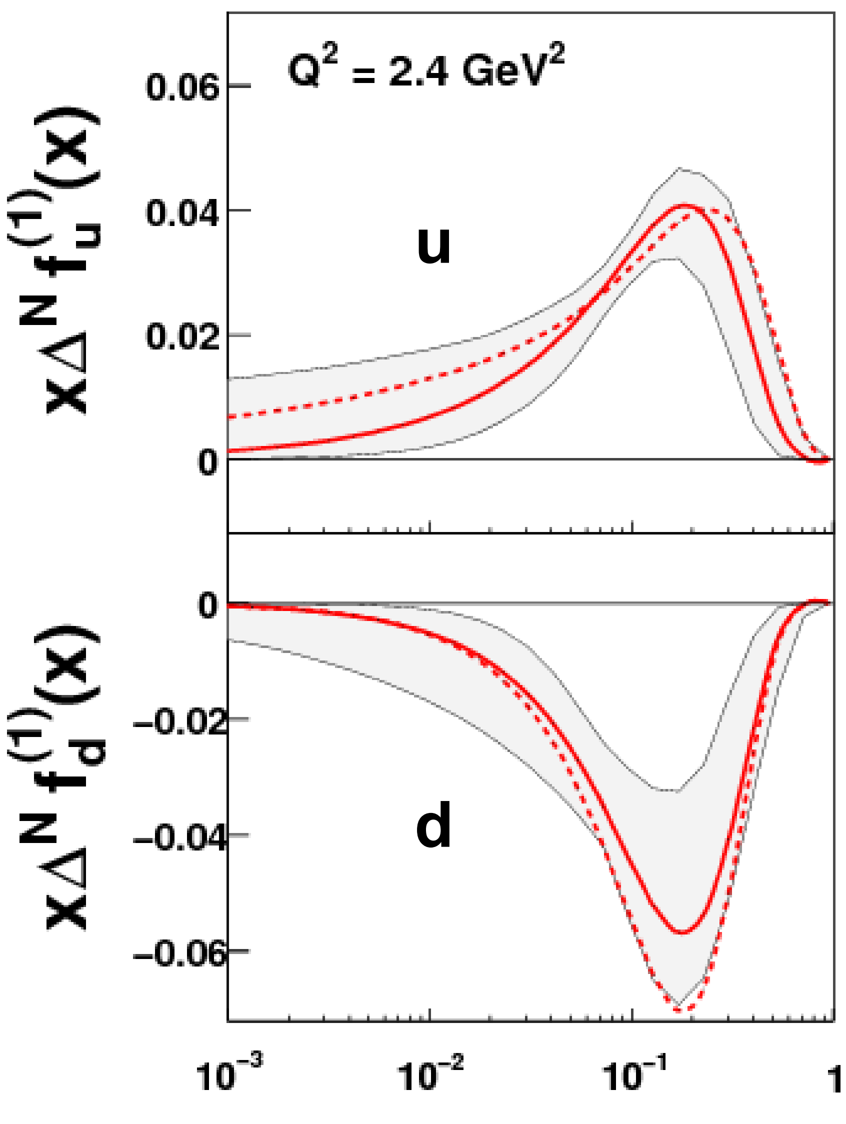
$$\Delta\sigma \propto A_{UT}^{\text{Collins}} \sin(\phi + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi - \phi_S)$$



Sivers function from SIDIS $\ell + p^{\uparrow} \to \ell' + \pi(p_T) + X: \quad p_T \ll Q$

- Extract Sivers function from SIDIS (HERMES&COMPASS): a fit





Anselmino, et.al., 2009

  - u and d almost equal size, different sign
  - d-Sivers is slightly larger

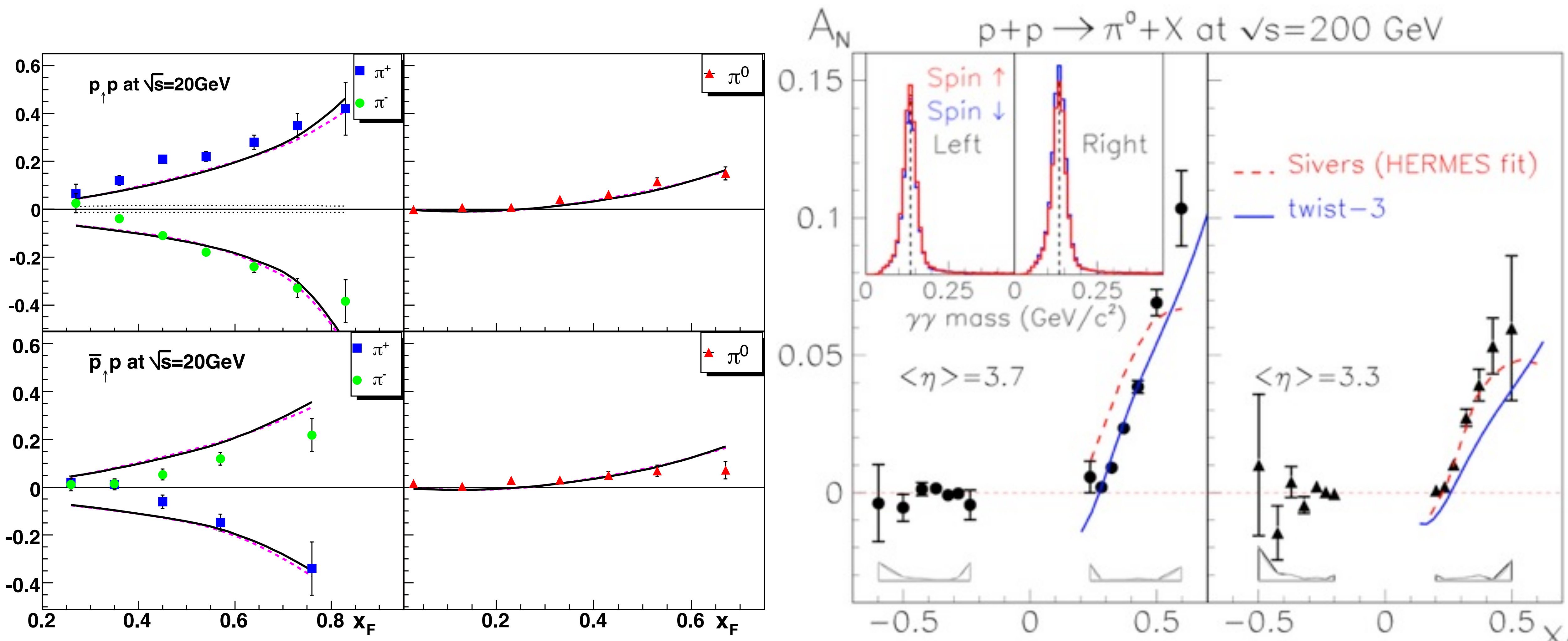
- Still needs DY results to verify the sign change, thus fully understand the mechanism of the SSAs

Initial success of twist-3 approach

- Describe both fixed-target and RHIC well: a fit

$$T_{q,F}(x,x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\phi_q(x)$$

Kouvaris-Qiu-Vogelsang-Yuan, 2006



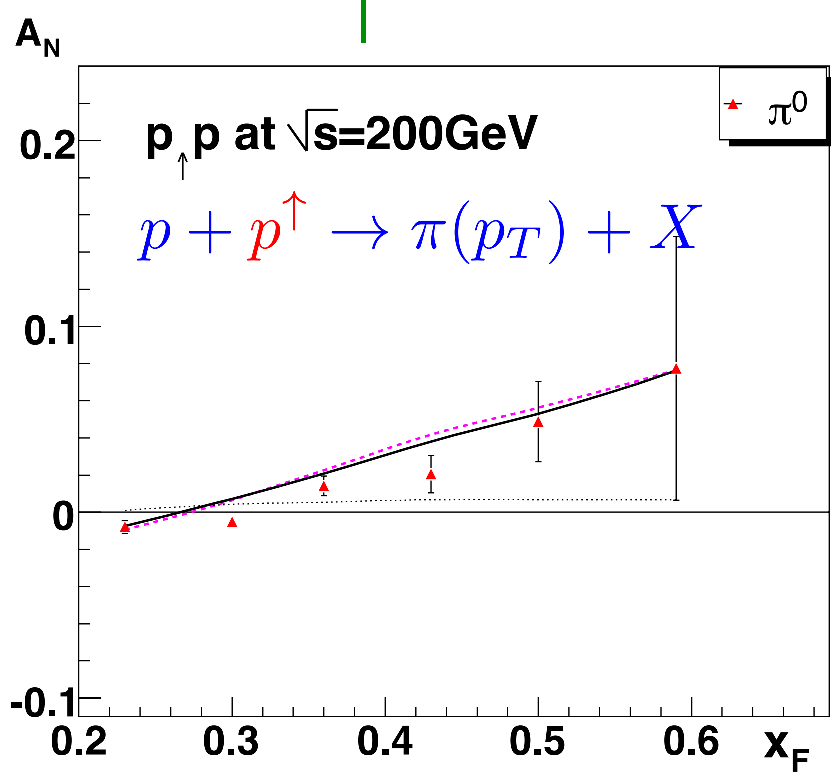
- See also the fit by Koike and Tanaka 2011

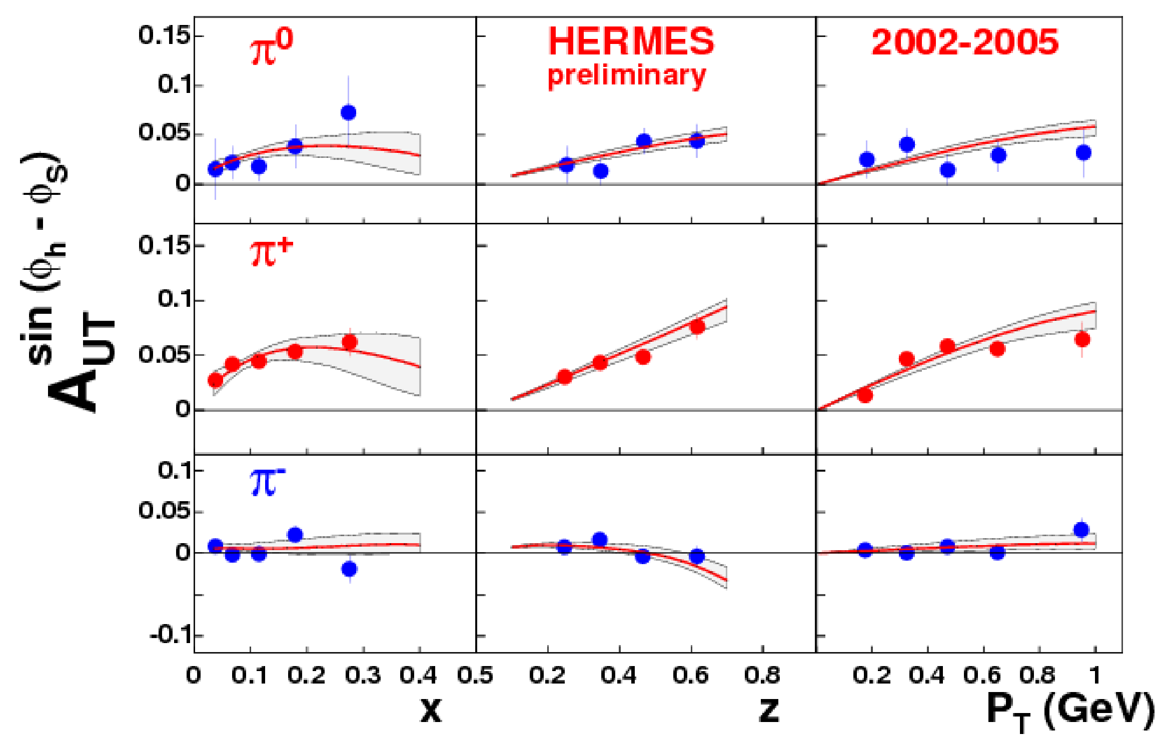
What about the connection?

- Both seem to describe the data well (in their own kinematic region), but what about their connections?
  - At the operator level, ETQS function is related to the first kt-moment of the Sivers function

Boer, Mulders, Pijlman, 2003
Ji, Qiu, Vogelsang, Yuan, 2006

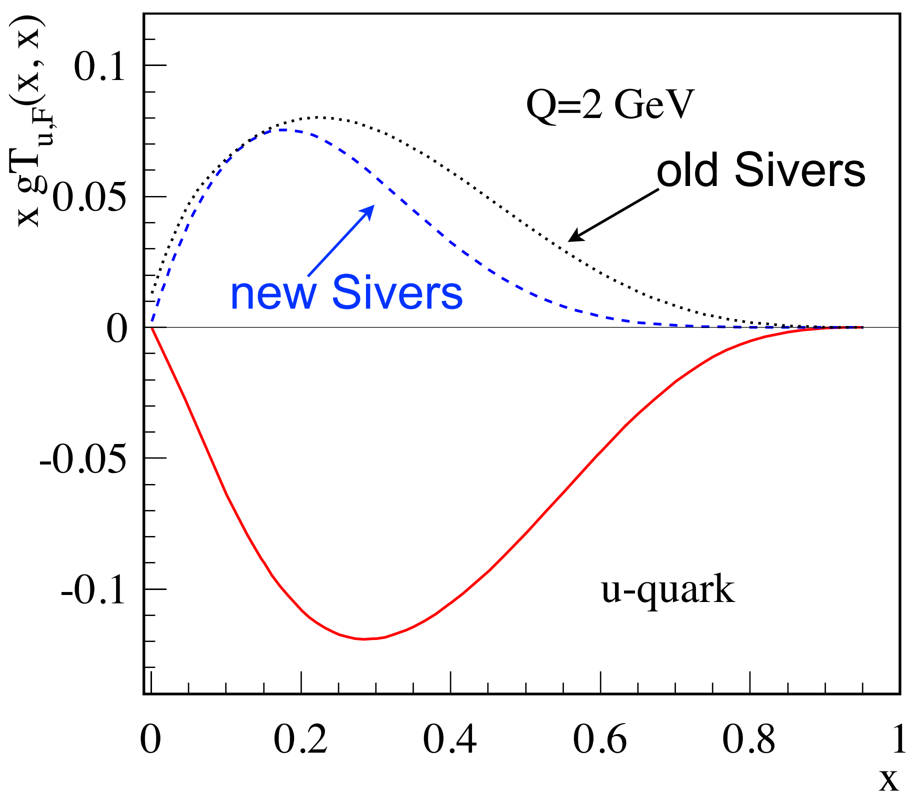
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

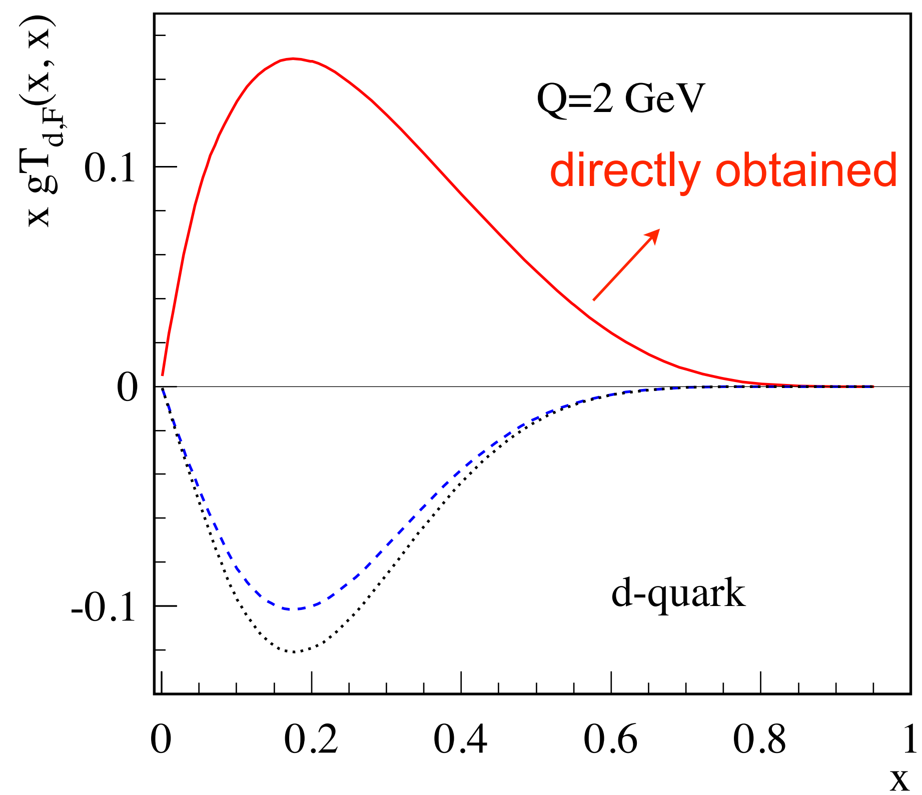




Directly obtained ETQS function

- ETQS function could be directly obtained from the global fitting of inclusive hadron production in hadronic collisions





- Basic observation:
  - SIDIS pi+: final-sate interaction
  - pp→pi+: initial-state interaction dominates in ug→ug

Question:

Are the SSAs of single inclusive hadron really coming from Sivers effect?

Global fitting of both SIDIS and pp data

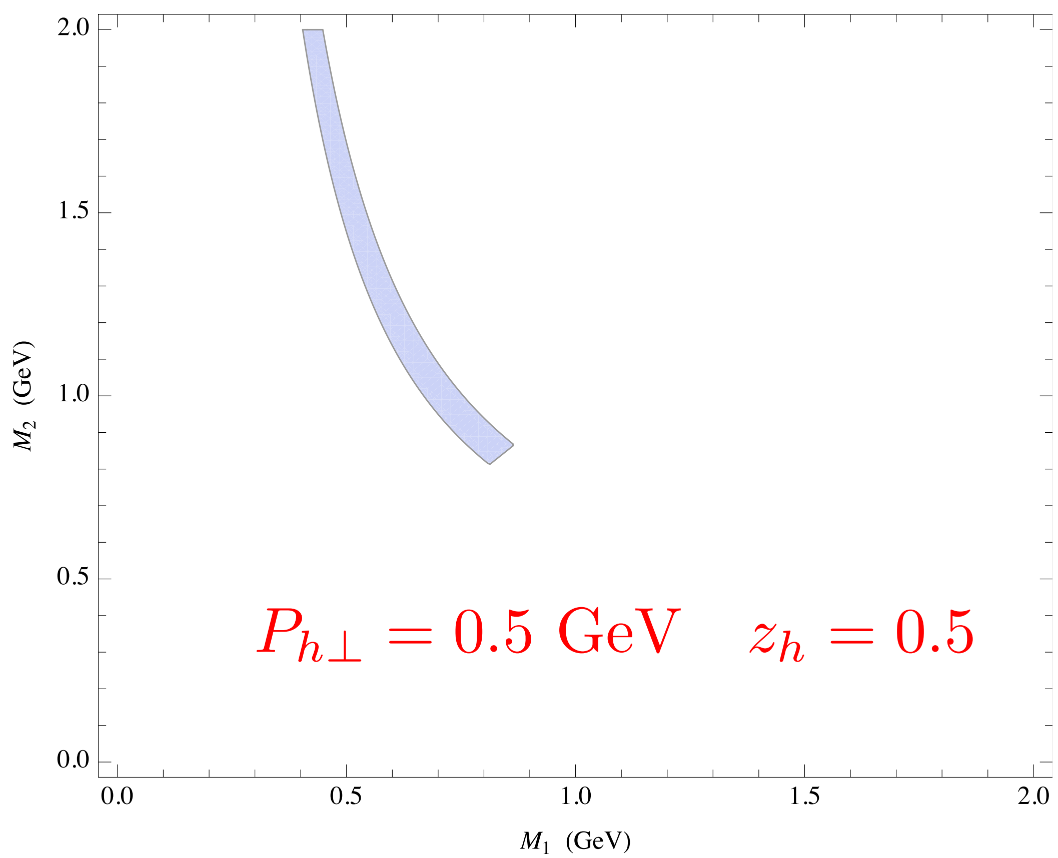
- Set-up

Kang-Prokudin, 1201.5427, PRD85, 2012

  - use TMD factorization for SIDIS Sivers asymmetry
  - use collinear twist-3 factorization for hadron asymmetry in pp
  - connect the fitting function $T_F(x, x)$ and Sivers function through

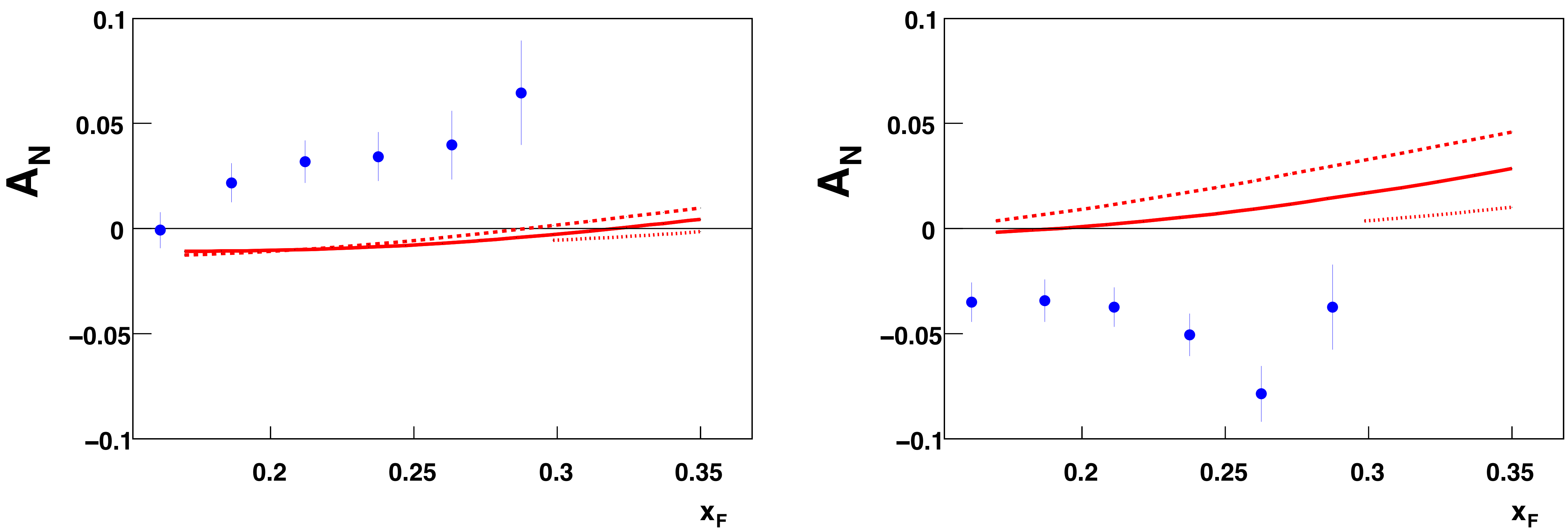
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

- Attempt I: node in kt (allowed parameter space is too small)



Global fitting

- Attempt II: node in x (fails to describe BRAHMS data)

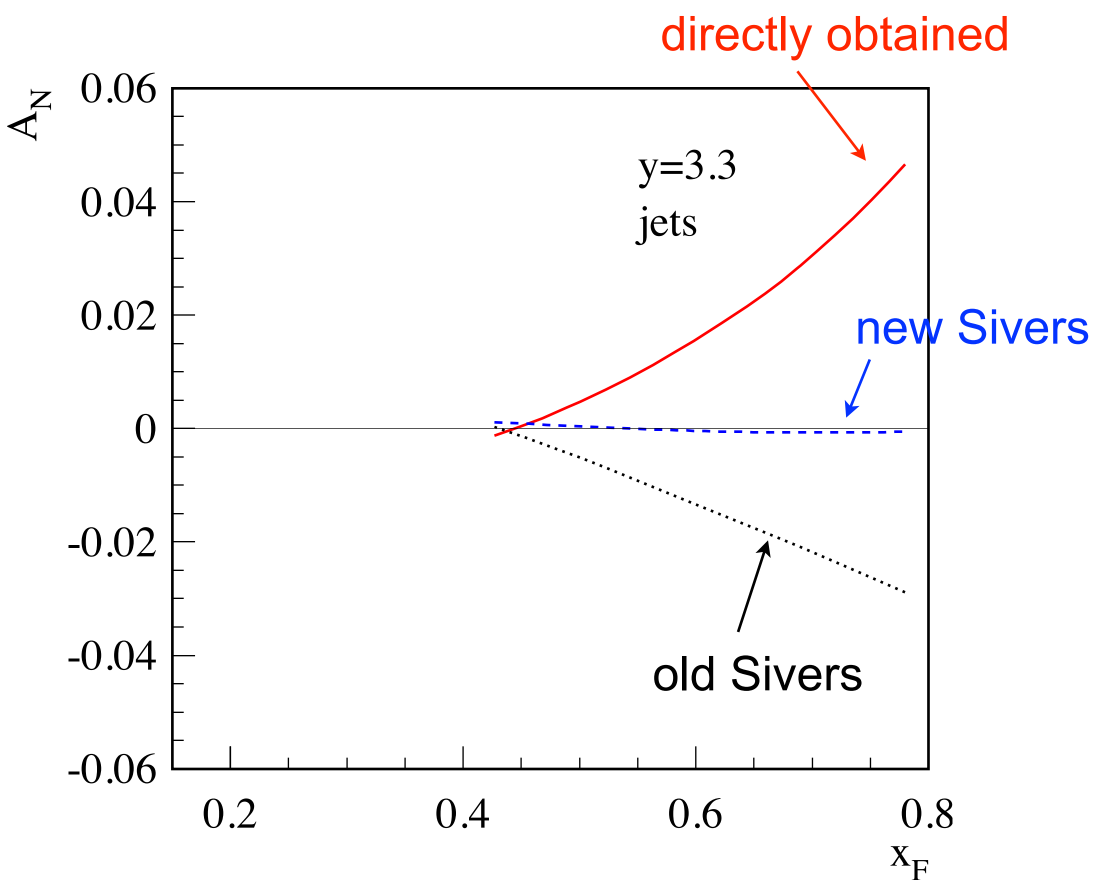


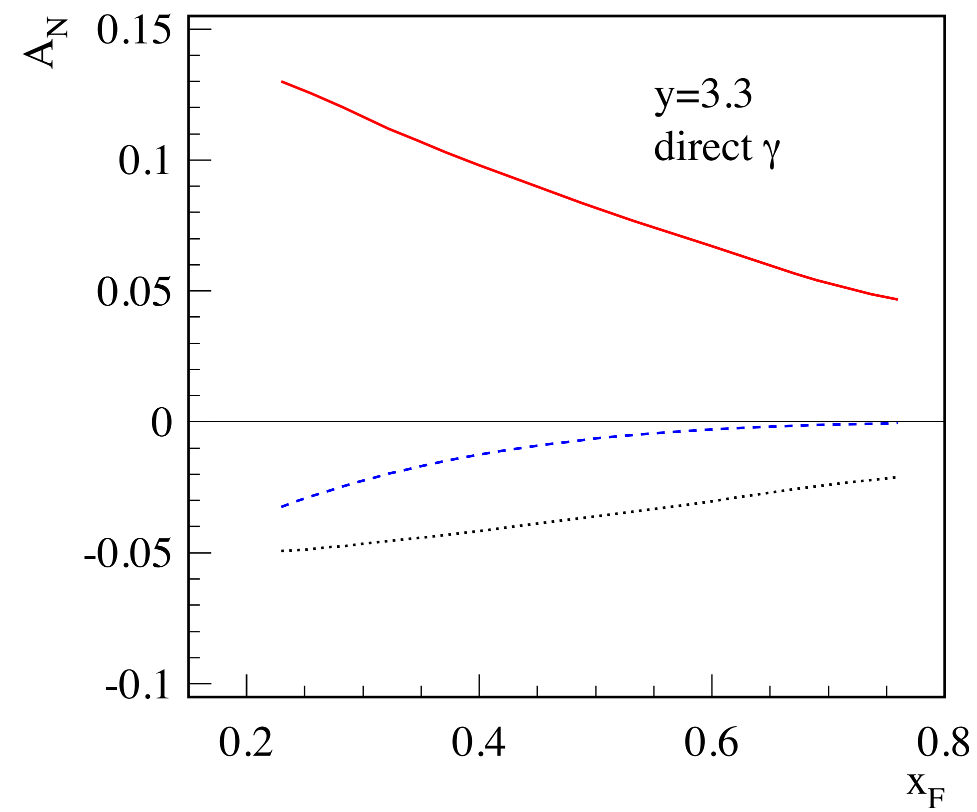
- Conclusion: the asymmetry of hadron production in pp might have nothing to do with Sivers effect. Then where does it come from? Collins effect?

Jet and direct photon: without complication of fragmentation

- at RHIC 200 GeV:

Kang-Qiu-Vogelsang-Yuan, 1103.1591, PRD83, 2012



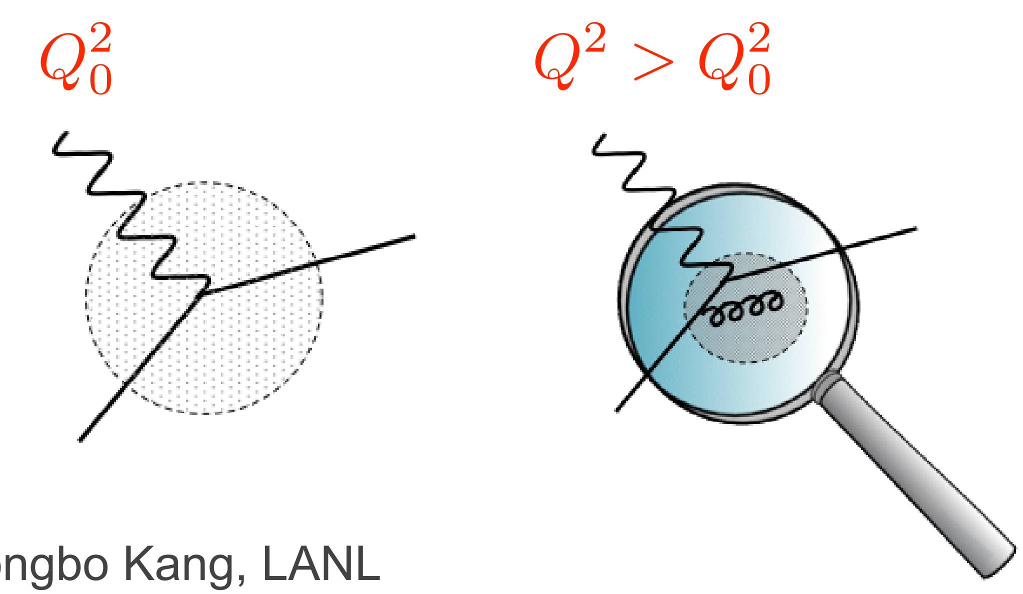


Evolution is a key test of QCD

- Evolution of twist-3 function $T_F(x, x)$
  - 2009: 4 groups have calculated the evolution equation of $T_F(x, x)$, Kang-Qiu, Yuan-Werner, Zhou-Yuan-Liang have the same result; different from Braun-Manashov-Pirnay
  - 2012: Braun-Manashov-Pirnay is correct after all

Kang-Qiu, 1205.1019, PLB, 2012; Schafer-Zhou, 1203.5293; Ma-Wang, 1205.0611

$$
\begin{aligned}
\frac{\partial T_{q,F}(x,x,\mu)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\Bigg\{ & P_{qq}(z)\, T_{q,F}(\xi,\xi,\mu) \\
& + \frac{N_c}{2}\left[\frac{1+z^2}{1-z}\left(T_{q,F}(\xi,x,\mu) - T_{q,F}(\xi,\xi,\mu)\right) + z\, T_{q,F}(\xi,x,\mu) + T_{\Delta q,F}(x,\xi,\mu)\right] \\
& - N_c\, \delta(1-z)\, T_{q,F}(x,x,\mu) + \frac{1}{2N_c}\left[(1-2z)T_{q,F}(x,x-\xi,\mu) + T_{\Delta q,F}(x,x-\xi,\mu)\right]\Bigg\}
\end{aligned}
$$



Evolution of TMDs: test sign change in DY

- DY will be probing Sivers function at a very different Q^2 from what has been measured from SIDIS.
  - Two parts: (1) sign change, (2) magnitude is the same when compared in the same energy scale

$$\Delta^N f_{q/h^\uparrow}^{\rm SIDIS}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\rm DY}(x, k_\perp)$$

  - One needs to develop the energy evolution equation
- For DY and SIDIS, in the region qt << Q, the fixed-order pQCD calculations contain large double-logs, which can be resummed to all orders through evolution equations for TMDs

$$\left(\alpha_s \ln^2 \frac{Q^2}{q_T^2}\right)^n$$

Rapid developments on TMD evolution and resummation

- Two equivalent approaches
  - resummation: can resum large contribution to all orders in strong coupling

Kang-Xiao-Yuan, PRL. 2011

$$\frac{d\sigma}{dx_B dy dz_h d^2P_{h\perp}} = \sigma_0 \left[F_{UU} + |s_\perp| \sin(\phi_h - \phi_s) F_{UT}^{\sin(\phi_h - \phi_s)}\right]$$

$$F_{UT}^{\sin(\phi_h-\phi_s)} = -\frac{1}{4\pi}\int_0^\infty db\, b^2 J_1(q_\perp b) W_{UT}(b, Q, x_B, z_h)$$

$$W_{UT}(b,Q,x_B,z_h) = e^{-S(b,Q)} \sum_q (\Delta C^T_{q/i} \otimes T_{i,F})(x_B, \mu = \frac{c}{b}) \times (D_{B/j} \otimes \tilde{C}_{j/q})(z_h, \mu = \frac{c}{b})$$

  - re-organize in terms of simple TMD-like formula

Aybat-Collins-Rogers-Qiu, PRD85, 2012

$$W^{\mu\nu} = \sum_f |\mathcal{H}_f(Q;\mu)^2|^{\mu\nu} \int d^2\mathbf{k}_{1T}\, d^2\mathbf{k}_{2T}\, F_{f/P^\uparrow}(x, \mathbf{k}_{1T}, S; \mu; \zeta_F)\, D_{h/f}(z, z\mathbf{k}_{2T}; \mu; \zeta_D)\, \delta^{(2)}(\mathbf{k}_{1T} + \mathbf{q}_T - \mathbf{k}_{2T})$$

Comments on SIDIS and DY

- The only difference comes from so-called coefficient function
  - leading order

$$\Delta C_{i/j}^{T(0)}(z, \mu = \frac{c}{b}) = \delta_{ij}\delta(1-z) \qquad \text{DY}$$

$$\Delta C_{i/j}^{T(0)}(z, \mu = \frac{c}{b}) = -\delta_{ij}\delta(1-z) \qquad \text{SIDIS}$$

  - at next-leading-order: well-known difference due to $Q^2>0$ (<0)

$$\Delta C_{i/j}^{T(1)}(z, \mu = \frac{c}{b}) = \delta_{ij}\left[-\frac{1}{4N_c} + \frac{C_F}{2}(\frac{\pi^2}{2} - 4)\delta(1-z)\right] \qquad \text{DY}$$

$$\Delta C_{i/j}^{T(1)}(z, \mu = \frac{c}{b}) = -\delta_{ij}\left[-\frac{1}{4N_c} + \frac{C_F}{2}(-4)\delta(1-z)\right] \qquad \text{SIDIS}$$

  - Thus in the full perturbative QCD region, Sivers between SIDIS and DY is not just a sign: it is interesting to study the consequence

Phenomenological study: concentrate on small qt part

- For small qt region, we could use the resumed formalism. Don't need to worry about Y-term.

- Only at small b-region (corresponds to large momentum), one can calculate the relevant coefficients perturbatively.

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} = \frac{\sigma_0}{2\pi} \int_0^\infty db\, b J_0(q_\perp b) W_{UU}(b, Q, x_A, x_B)$$

$$W_{UU}(b, Q, x_A, x_B) = e^{-S(b,Q)} \sum_q e_q^2 (C_{q/i} \otimes f_{i/A})(x_A, \mu = \frac{c}{b})$$
$$\times (C_{\bar{q}/j} \otimes f_{j/B})(x_B, \mu = \frac{c}{b})$$

- However, in order to Fourier transform back to qt-space, we need the whole b-region. Since large b-region will be non-perturbative, we need a non-perturbative input. This part should be universal if QCD factorization holds for the process.

The parametrizations for the non-perturbative function

- Different approaches for the non-perturbative functions

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} = \frac{\sigma_0}{2\pi}\int_0^\infty db\, b J_0(q_\perp b) W_{UU}(b, Q, x_A, x_B)$$

$$W_{UU}^{pert}(b, Q, x_A, x_B) = e^{-S(b,Q)} \sum_q e_q^2 (C_{q/i} \otimes f_{i/A})(x_A, \mu = \frac{c}{b})$$
$$\times (C_{\bar{q}/j} \otimes f_{j/B})(x_B, \mu = \frac{c}{b})$$

- Parametrize the full b-space function

$$W_{UU}(b, Q, x_A, x_B) = W_{UU}^{pert}(b, Q, x_A, x_B) F^{NP}(b, Q, x_A, x_B)$$

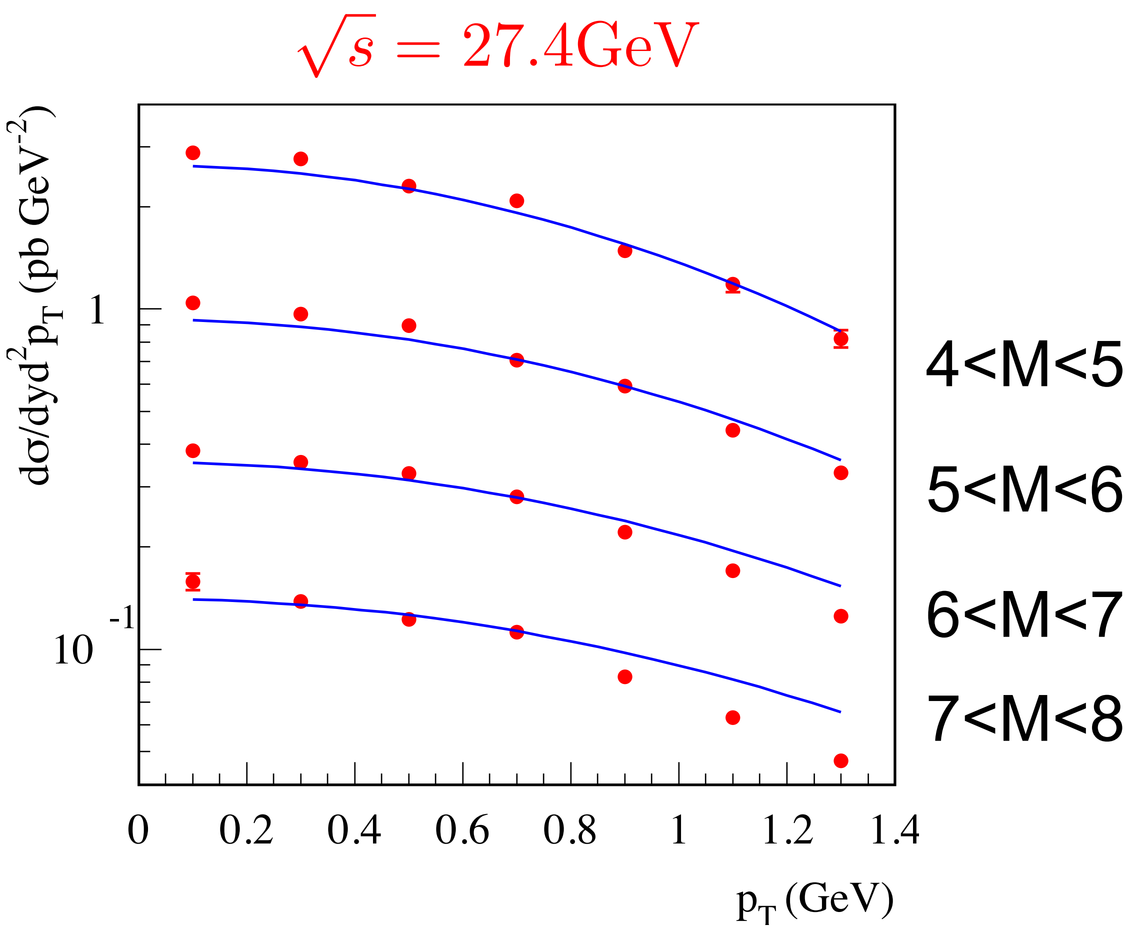
  - function form (through extrapolation): Qiu-Zhang, 2001
  - fitted form directly from experiments: Brock-Landry-Nadolsky-Yuan, 2003

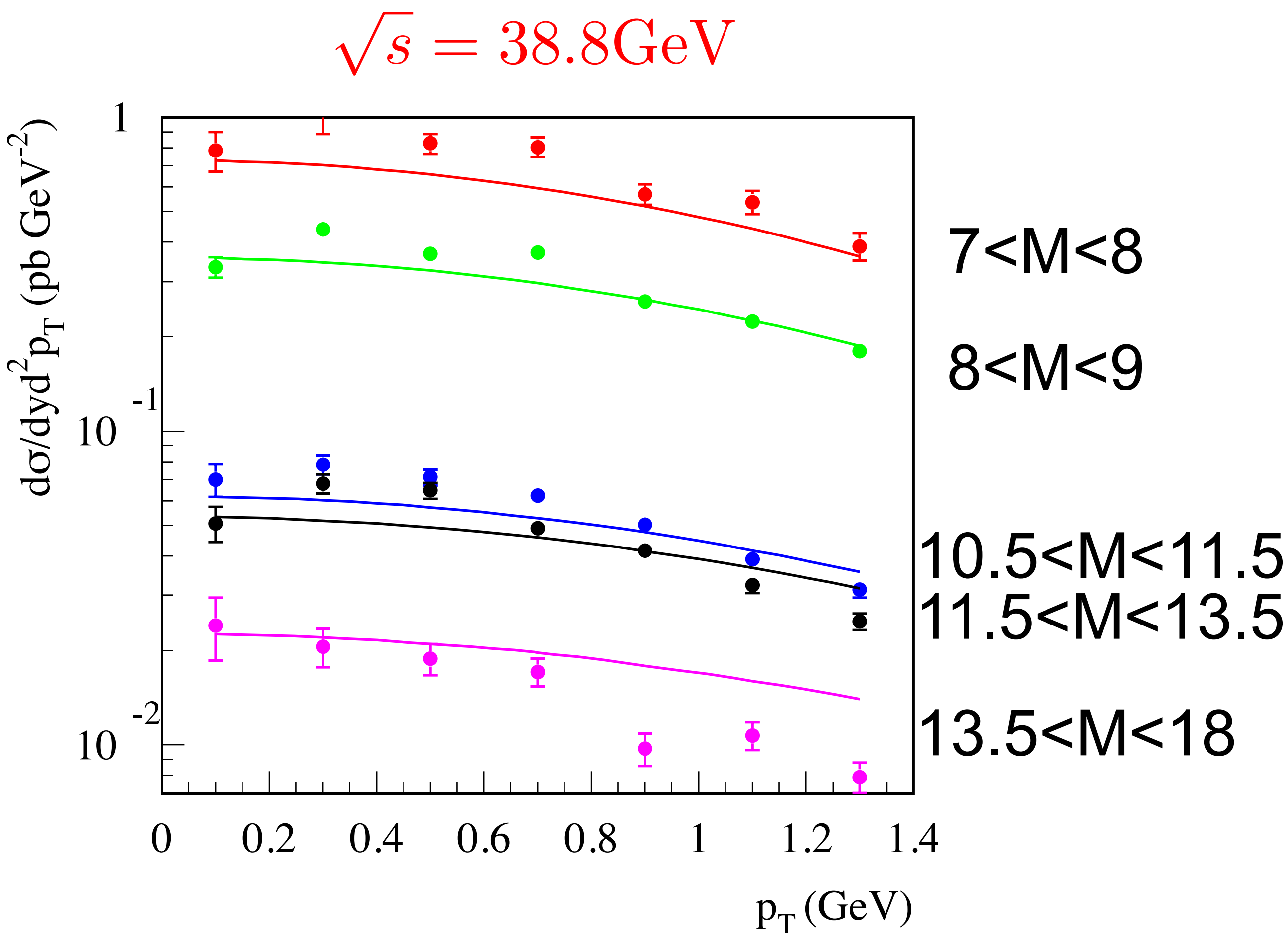
$$W_{UU}(b, Q, x_A, x_B) = W_{UU}^{pert}(b_*, Q, x_A, x_B) F^{NP}(b, Q, x_A, x_B) \quad b_* = \frac{b}{\sqrt{1 + (b/b_{max})^2}}$$

$$F^{NP}(b, Q, x_A, x_B) = \exp\left\{-\left[g_1(1 + g_3 \ln(100 x_A x_B)) + g_2 \ln\left(\frac{Q}{2Q_0}\right)\right] b^2\right\}$$

Resummation formalism works well for cross section

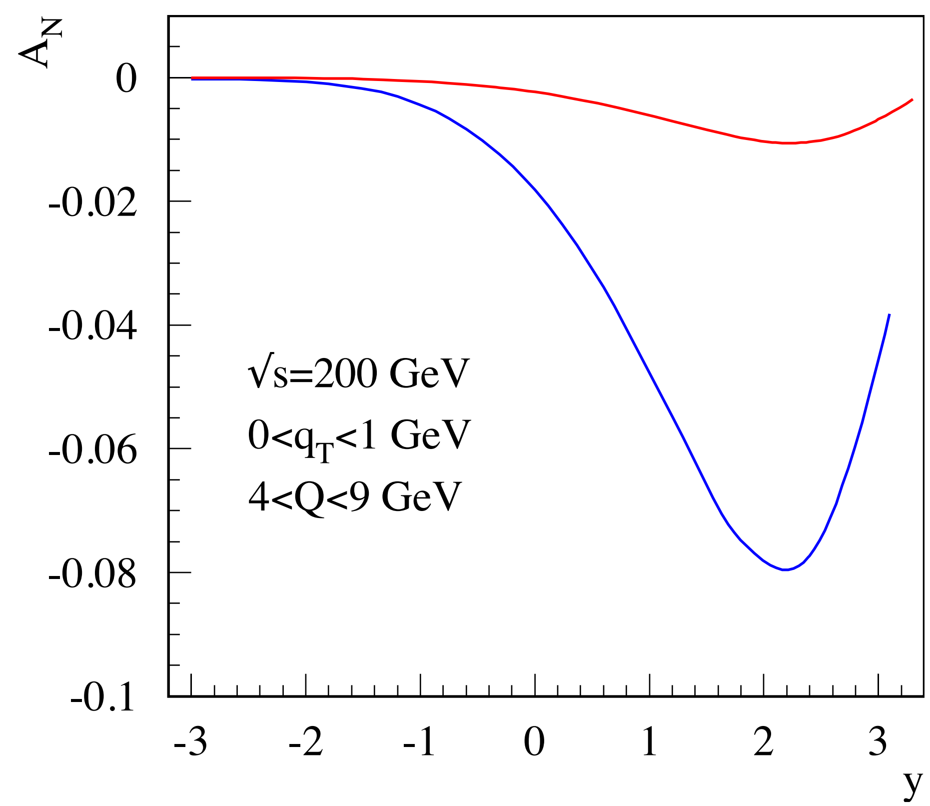
- E288 and E605





Sivers effect of DY production at RHIC

- Blue curve: bare parton model (using Torino TMD with Gaussian ansatz from SIDIS)
- Red curve: resummed formalism (using Torino TMD to calculate $T_F(x, x)$ as the initial input function, then evolve)



- caution: (1) non-perturbative part could be different for Sivers asymmetry; (2) so far the non-perturbative part is fitted from high Q data, need a refit (adjustment) for the low Q Sivers data

Other developments

- Study of gluon distributions
  - gluon's role in generating spin asymmetry: direct photon at negative xf, and etc; open charm production

Koike-Yoshida, 1104.3943, 1112.1161

$$O^{\alpha\beta\gamma}(x_1,x_2) = -g(i)^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle pS| d_{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n)|pS\rangle$$

$$N^{\alpha\beta\gamma}(x_1,x_2) = -g(i)^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle pS| i f_{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n)|pS\rangle$$

  - gluon "Boer-Mulders" function: gluon with linear polarization in unpolarized hadron (T-even): Higgs production, diphoton, heavy flavor, ...

"Boer Mulders"

$$\Gamma_U^{+i;+j}(x,\vec{k}_T) = \frac{\delta^{ij}}{2} f_1^g + \frac{k_T^i k_T^j - \frac{1}{2}\vec{k}_T^2 \delta^{ij}}{2M^2} h_1^{\perp g}$$

Boer-Brodsky-Mulders-Pisano, Qiu-Schlegel-Vogelsang, Boer-den Dunnen-Pisano-Schlegel-Vogelsang, Sun-Xiao-Yuan

Summary

- We are making steady progress on spin physics
  - longitudinal spin: gluon might have non-vanishing contribution to proton spin
  - transverse spin: we need more data
- Quite some progress on the theory side
  - connection between SIDIS and pp: sign mismatch, need experiments to give guidance now
  - QCD evolution is still under active development: stay tuned
- Besides probing spin structure of the proton, spin is also a useful tool to study QCD dynamics, which turns out to be exciting these days

Summary

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Thank you